Completion Report
Cooperative Agreement INT-81-134-CA

DEVELOPMENT AND TRIAL APPLICATION OF THREE LEVEL COMPUTER BASED LANDSLIDE ANALYSIS SYSTEM

Between

U.S. Forest Service, Intermountain Research Station

and

University of Idaho, College of Mines and Earth Resources

by
Terry R. Howard

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Introduction

This Cooperative Agreement between the U.S. Forest Service Intermountain Research Station and the University of Idaho, College of Mines and Earth Resources was started in August of 1981 with the general objective of developing a computer-based three-level landslide evaluation system. The system was to be used by both geotechnical engineers and resource planners to assess the effect of resource harvesting on natural slope stability. An idealization of the three-level slope stability analysis system is presented on Figure 1. We also were to assist in the preparation study plans for Levels 1, 2, and 3.

The initial study plans were submitted to the Forest Service under cover letter dated September 19, 1983. The study plans were reviewed by the Forest Service and were jointly completed after several revisions and associated reviews by both the Forest Service and the University of Idaho. The final study plans were submitted for approval in August of 1984 and were approved in July of 1985.

The three study levels were to be associated with computer programs for each level. Level 1 was originally based upon Simon, Lee and Ward's work (1978) using an infinite slope stability model. The anticipated master program structure for Level 1 is shown on Figure 2. The original aim was to digitize polygons from land type maps as input into the slope stability program. The land type polygons would be associated with all the input factors necessary for calculations of probabilities of failure or factors of safety against failure. The output would be displayed in numerical sequences associated with the polygon and would be presented as gray scale maps of the study area. A digitizer for inputing polygon information and a plotter for output were purchased by the University with

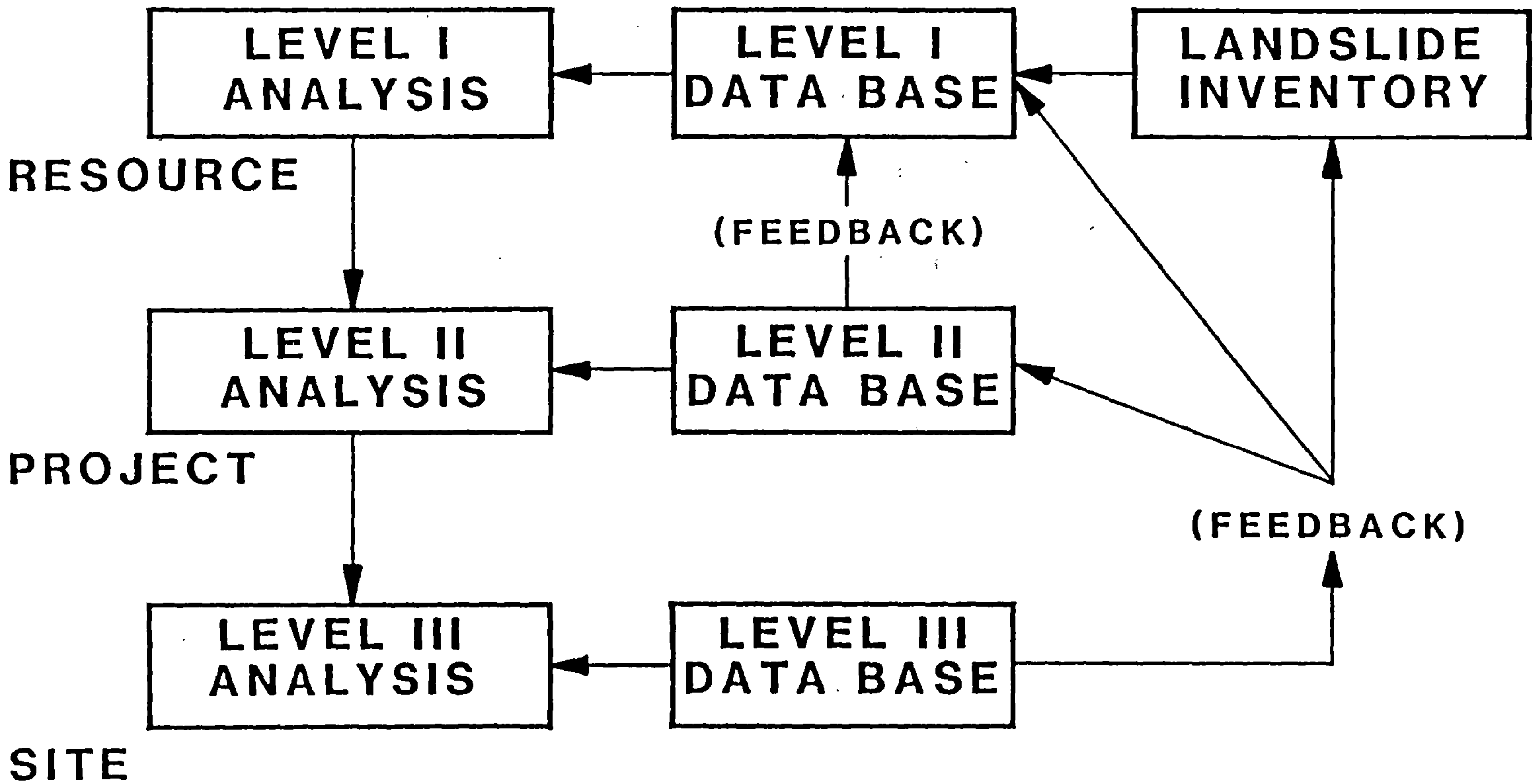


Figure 1.--Idealized three-level slope stability analysis.

LEVEL 1 SYSTEM FLOW CHART

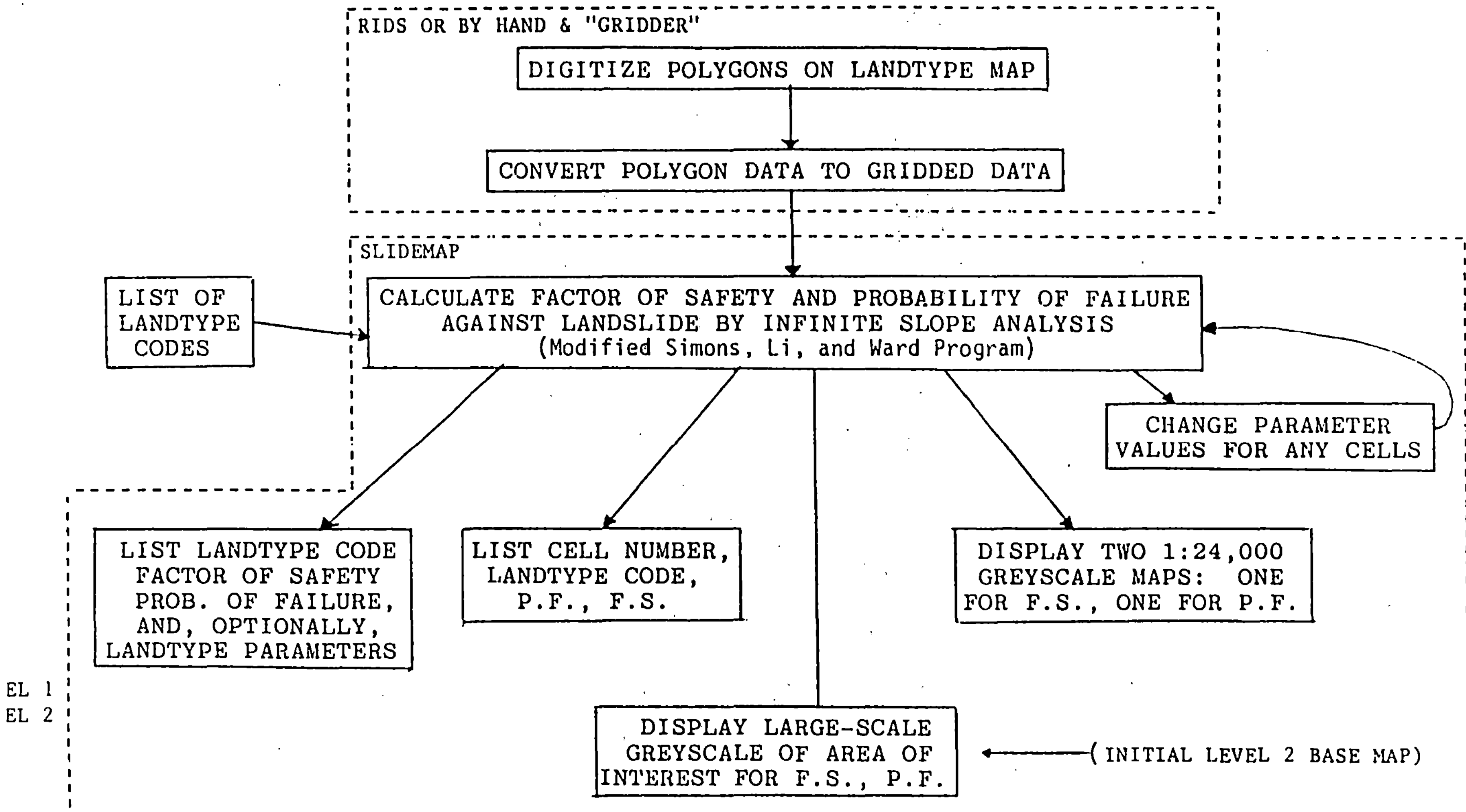


Figure 2. Anticipated master program structure for Level No. 1

the agreement that they would be returned to the U.S. Forest Service after completion of the University work. These two purchases were returned to the Intermountain Station in Moscow, Idaho this year.

The coding of the Level 1 analysis was completed in late 1981 and early 1982. The code was checked using a test project from the Clearwater National Forest.

During 1982, Rod Prellwitz authored a paper for presentation at the annual meeting of the Transportation Research Board in Washington, D.C. The paper was co-authored by Terry R. Howard, University of Idaho, and Dale Wilson, Clearwater National Forest. This paper was the first formal documentation of the three-level slope stability concept and was used extensively in the preparation and refinement of study plans 1, 2 and 3.

During this time period discussions were held with colleagues and Forest Service engineers in the Pacific Northwest to design the idealized three-level slope stability analysis presented in Figure 1. It was obvious that a feedback loop was necessary in order to obtain more accurate input information for the Level 1 and Level 2 analyses. It was conceived that the feedback information could be obtained from Level 3 analysis and fed into Level 2 and finally back to Level 1. It was also obvious that the feedback information must be somehow protected in the computer environment. Work on this concept was carried out over the next several years as shown by Item 1.

Rod Prellwitz completed the first draft of an HP41 program for the Level 2 analysis. This program was reviewed by the University of Idaho and a user's guide was begun for both Level 1 and Level 2. Documentation for the Level 1 and Level 2 analysis continued as the programs were used and subsequently modified. These user manuals were submitted to the

Forest Service in rough draft form in 1984, a copy of both are attached as Items 2 and 3.

Continued work with the Level 1 program during 1983 indicted that there were problems with the probability of landslide occurrence in the program. These problems were identified using a test plot from the Clearwater National Forest. The extent of the problems were discussed with Forest Service personnel and ideas to modify the program were considered.

Initial work for the Level 3 analysis began in 1983. The Level 3 analysis was supposed to be an accurate portrayal of the geometry and ground water of the site and produce a relatively accurate factor of safety for a site specific analysis. Because of numerous programs already coded it was decided that Level 3 would be based upon an existing program. The program selected for Level 3 analysis was STABL3, a program developed for the U.S. Department of Transportation by Purdue. A copy of this code was acquired in 1983 and, since it was coded for mainframe application, we provided the necessary reprogramming for operation on PCs.

Nineteen eighty-four was spent documenting Level 1 and Level 2 programs. The documentation produced that year is attached. Please recognize that this documentation was dynamic in that as we continued to upgrade the programs, we also continued to upgrade the user manuals. The U.S. Forest Service Intermountain Research Station in Moscow has the latest edition of the user's guide for both Level 1 and Level 2 programming.

During this period we began to test the Level 1 program on a test project on the Gallatin National Forest in Montana. Mr. Henry Shovic had a test program that incorporated all of the input parameters necessary for

the Level 1 program, plus he had mapped the landslides in the test area. An example of this information is in Item 4. The results of our analyses indicated that the probability of landslide occurrence was not giving realistic values. Several meetings with Forest Service and University of Idaho engineers, statisticians, mathematicians and geotechnical engineers were held in order to solve this problem. Our work on this problem continued into the next year.

In 1985, our contract was amended in order to incorporate the findings from the previous four years work. These findings indicated that the manner in which the probability of landslide occurrence was computed was not appropriate. Therefore a redirection was necessary for all three levels of study. In order to resolve this problem, a meeting was held at the University of Idaho on February 8, 1985. A copy of the announcement of this meeting is attached as Item 5. During the meeting those present reviewed the deterministic approach and discussed and evaluated applicable probabilistic methodologies to include in the three levels of study. This discussion resulted in the modification of our general contract in order to incorporate specific items for probabilistic analysis in each of the three study levels.

For study number one, the study of Gallatin National Forest was completed. Based upon the trial application, the method was reevaluated and the method of calculating the probability of landslide occurrence was changed by adding a Monte Carlo procedure to select input variables for the program. The addition of Monte Carlo analyses to the Level 1 program included independent soil variables. These changes were developed and programmed. Testing for this procedure began immediately. See Items 6 and 7.

For study Level 2 we began to incorporate a graphics display system. We also began to program a feedback loop from the Level 3 into the Level 2 and Level 1 analysis and from the Level 2 into the Level 1 data base. Within the same time period we reevaluated the alternative methods to analyze probability of landslide occurrence in Level 2 as we did for the Level 1 approach. The same conditions applied and the same general Monte Carlo approach was selected as the most applicable technique. Additional work was accomplished on Level 2 by Rod Prellwitz to include the Cousins' Method in the program.

Study 3 included considerable work to modify the program. STABL3 did not include corrections to the phreatic surface or to Janbu's Method of analysis as discovered by Mr. Prellwitz. We also discovered several other problems in the code that needed correction. Noteworthy was the inability of the code to perform deterministic analysis while incorporating earthquake force in the computations. These problems were discussed with the original program developers at Purdue and we then began to incorporate them into our version of the STABL3 program. We also changed the random number generator in the program as documented by Item 8. It should be noted that the original developers at Purdue did not concur with our suggested changes.

Our probabilistic approach for Study 1 and Study 2 also apply to Study 3. We evaluated the alternative methods to analyze probability of landslide occurrence for Level 3 and selected the Monte Carlo technique again. At the same time it became apparent that the shear strength parameters c and ø were connected by our laboratory techniques in evaluating these parameters. Therefore, we needed to evaluate a technique for reducing the statistical errors which resulted from considering soil

cohesion, c, and soil internal angle of friction, ø, as separate independent variables. In other words, it was necessary to develop a technique for linking c and ø values in the geostatistical analysis. This was accomplished by Professor Stan Miller and was programmed into Level 1. The Level 1 data base then was the beginning for the Level 3 feedback loop.

The user's guides for Level 1 and Level 2 were continually modified and updated during this period. We continued to use Purdue's User's Guide for STABL3 since the modifications we incorporated into the Level 3 program involved corrections to the code rather than modifying the methods for input/output.

The work begun in 1985 was significant and provided major direction to each of the three levels of study. This work was continued into 1986 by adding to the documentation for User's Guides for Levels 1, 2, and 3.

We also completed the reprogramming and documentation of the modifications to STABL3. The copy of the Level 3 modifications is attached as Item 9. Our work in this area caused some discontentment in the general geotechnical engineering community. We therefore made a presentation to the FHWA Northwest Geotechnical Engineering Workshop held in Helena, Montana that year. The presentation was given by Rod Prellwitz and Terry Howard, and described the reasons we felt the modifications to the Level 3 program were necessary and also describe the modifications that were made (Item 10).

The changes that were made to the probabilistic method of analyzing landslide occurrence in each of the three levels was significant during the years of 1985 and 1986. Professor Stan Miller, a geostatistician by training and a recent addition to the University of Idaho faculty, was

instrumental in these changes. By 1987 he had essentially taken over the direction of the Coop. The objectives for 1987 were to complete a trial application and begin the technology transfer for the Level 1 stability analysis. At the same time ground water precipitation monitoring began two years earlier by Mr. Prellwitz on sites in the Clearwater National Forest, were completed by Professor Miller. These studies were most valuable in providing the statistical data necessary to implement the Level 1 statistical modeling. Ground water data for the Dan Lee and Lean To Ridge sites in the Clearwater National Forest are attached.

Perhaps the most significant output in this final year was the beginning of the technology transfer to the Forest Service personnel. This occurred in March of 1987 on the University of Idaho Campus in the form of a short course to introduce general geostatistical methods and the Level 1 and Level 2 analysis. A copy of the manual entitled "An Introduction to Probabilistic Analysis for Geotechnical Engineering Applications in Design Making" is attached and completes this report (Item 11).

Item 1

PROPOSED FEEDBACK SYSTEM -- LEVEL II TO LEVEL I

DAVID HALL   OCTOBER 1985

GENERATING THE FILE

From within Level II program, after infinite slope analysis on a site has been performed (so the user can determine whether the data used were satisfactory), if the user desires, append to the FEEDBACK FILE: the landtype code representative of the site, the parameter values used, and a short comment (user name, other particulars).

DATA TO BE STORED IN FILE

The following variables will be represented in the feedback file:

```
Y    -- soil density (normal)     (pcf)
Ysat -- soil density (saturated)  (pcf)
H    -- soil depth                (feet)
B    -- surface slope             (degrees)
Cr   -- root cohesion             (psf/ft)
```

This covers all of the primary random variables in the Level I analysis with the exception of tree surcharge, q0.

USING THE FILE

The Level I file will not be updated or modified automatically. Instead, a user may at any time run a program which will analyze the values stored for each parameter for any or all entries in the feedback file for a particular landtype code. The user may then modify the landtype code file permanently, or make temporary changes while running the Level I SLIDES program, based on the distributions found in the feedback file.

It should be noted that it is important to keep track of how the landtype code files are modified, and by whom, in order to keep any integrity in the data and the resulting modelling predictions. Thus, some type of system should be devised which allows only responsible people with "good" data to modify generally used files, and then only if everyone is advised of the modifications.

```
USER ENTERS LANDTYPE CODE TO EXAMINE
PARAMETERS FOR ALL ENTRIES WITH THIS CODE ARE READ FROM DISK;
     VALUES AND COMMENTS ARE DISPLAYED
ALLOW USER TO DISALLOW ANY ENTRIES WHICH LOOK SUSPECT
CHOOSE A PARAMETER TO STUDY
DISPLAY A SCATTER DIAGRAM FOR ALL ALLOWED ENTRIES
ALLOW USER TO DISALLOW ANY SUSPECT ENTRIES
ROUND PARAMETERS TO INTEGER; DISPLAY HISTOGRAM (MIN..MAX) FOR
     REMAINING ENTRIES
DISPLAY MEAN, STD DEV, MIN, MAX
```

LANDTYPE CODE PARAMETERS

γ_{moist} γ_{SAT} are dep by an equation.

- IN .LTC FILE:

  tree surcharge
  Soil density – ~~dry~~ moist
  soil density – ~~saturated~~ satur.
  soil depth
  ground surface slope — %
  root strength

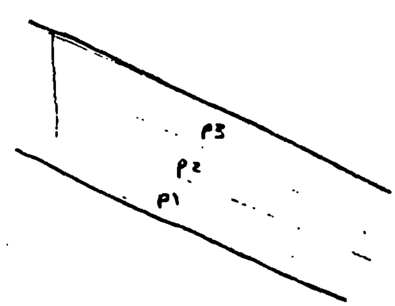
- IN .TAU FILE:

ϕ mean	coeff of friction
ϕ s.d.	"
c mean	cohesion
c s.d.	"

  cov [TAN ϕ, c]

- IN .HYD FILE:

  soil intervals (#, prob gw in each)
  yields values for groundwater depth



$\sum p_i = 1.00$

VSC DATA:

ENTER: $E[\phi]$, $SD[\phi]$, $E[c]$, $SD[c]$, $COV(TAN\,\phi, c)$

$E[TAN\,\phi] = TAN(E[\phi])$

$VAR[TAN\,\phi] = (TAN(SD[\phi]))^2$

$E[C]$

$VAR[C] = (SD[C])^2$

$COV[TAN\,\phi, C]$

STORED IN FILE

$COV[\mu, c] =$

$$\frac{1}{n-1}\left[\sum^{n} \mu_i c_i - \frac{1}{n}\left(\sum^{n} \mu_i\right)\left(\sum^{n} c_i\right)\right]$$

for n data points

$$E[\tau] = \sigma E[TAN\,\phi] + E[C]$$

$$VAR[\tau] = \sigma^2 VAR[TAN\,\phi] + VAR[C] + 2\sigma\, COV[TAN\,\phi, C]$$

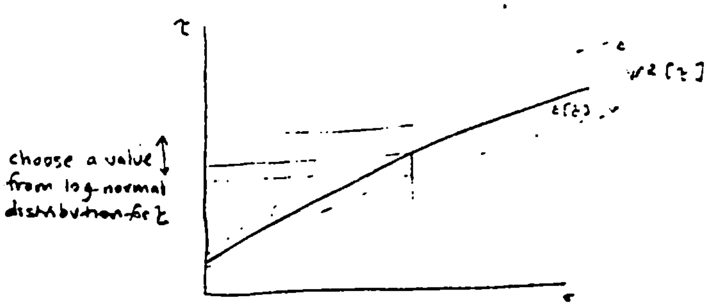
TEST DATA:

START WITH SERIES OF σ-τ VALUES FROM SEVERAL SAMPLES

$n, a, b, c, \overline{XINV}, \overline{XTXS}$ STORED IN FILE

$$E[\tau] = a\sigma^b + c \qquad \overline{X} = \begin{bmatrix} \sigma^b \\ \sigma^b \cdot \ln(\sigma) \\ 1 \end{bmatrix}$$

$$VAR[\tau] = (((\overline{X}^T \cdot \overline{XINV}) \cdot \overline{XTXS}) \cdot \overline{XINV}) \cdot \overline{X}$$



~~(144.16~~ 2 17

$(144 \cdot .4)^2$ 30c

psf

v : psf 2

Item 2

S S I S C H

LEVEL II LANDSLIDE HAZARD PROGRAM

INFINITE SLOPE AND CRITICAL HEIGHT

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College of Mines and Earth Resources
University of Idaho, Moscow Idaho

May 1984

SCOPE

SSISCH is a computer program which calculates the factor of safety against landslide of a site, using an <u>infinite slope</u> analysis. The data used for this analysis may be manipulated until a reasonable result is produced, whereupon a roadcut may be overlaid on the slope. SSISCH will then calculate the stability of the proposed roadcut using a <u>critical height</u> analysis.

SSISCH is intended to be used as a "level 2" analysis tool; that is, it is used to analyze potentially critical sites at more detail than is done with the broader "level 1" analysis. While the level 1 analysis uses ranges of soil, slope, and vegetative data broadly related to landtype codes, the level 2 analyses use measured or more closely estimated values for the same data. Additional data are also required. However, the level 1 landtype database may be accessed through SSISCH, and the user is allowed to make any modifications to that data which he desires. The changes will not be made permanently in the database, but future versions of SSISCH will allow feedback to the level 1 database of the knowledge gained by level 2 analyses.

Two road templates are supplied for use with SSISCH: a full-bench roadcut and a self-balanced roadcut. In addition, a user-defined geometry may be specified. The roadcut, overlaid on the ground slope and phreatic surface, may be plotted on the color graphics monitor.

SSISCH (Slope Stability analysis by Infinite Slope and Critical Height) was originally written for the Hewlett Packard HP-41CV handheld computer by Rod Prellwitz of the Intermountain Forest and Range Experiment Station, Missoula MT. It has been greatly enhanced and modified to run under Microsoft's version of the FORTRAN IV computer language on a microcomputer in an interactive environment.

PROGRAM DESCRIPTION

SSISCH is used to perform a site-specific analysis of factor of safety against landslide followed optionally by a critical height analysis of an overlaid roadcut. Thus, it is a level 2 tool using parameters measured or estimated for a particular site, as opposed to using general estimates based upon a landtype code.

Data entry is easy and flexible. All site and roadcut data are entered through an appropriate menu, allowing values to be entered in any order and modified any number of times until you are satisfied. After an analysis is performed, you are given the option to run another analysis using modified data. Only those values which you wish to change have to be entered.

All site and roadcut parameters have default values at the outset. Most of the site parameters may be read from a SLIDES landtype code file by specifying the file name and the landtype code to be used. SSISCH will display all codes present in the landtype code file to help in specifying the proper code. No matter which data are used initially, you have full control to modify the values in any way.

Once the site data have been entered, you may either run an infinite slope analysis or proceed to enter roadcut data and optionally run a roadcut analysis. After any analysis, you may modify site data or roadcut data and perform another analysis. After the roadcut analysis, you may plot on the color graphics monitor a cross-section of the site showing ground surface, phreatic surface, and root and soil depth, along with the roadcut overlaid upon the ground surface. Finally, a report may be printed on the printer.

The roadcuts may use a full-bench or a self-balanced template, or a user-defined geometry may be used. Entry for roadcut data is similar to entry of site data, with the user having full control over the order in which entries are made, and how many times parameter values are changed. You may easily switch among full-bench template, self-balanced template, and user-defined geometry. Only the relevent parameters are requested based upon the chosen template, and values entered for parameters related to one template are not lost when you switch from template to template.

The roadcut analysis estimates the values for the <u>stability number</u> (N), and the <u>critical cut height</u> (Hc) for the proposed roadcut, and declares whether the roadcut is stable or unstable. The roadcut's stability number is developed from curve fitting done by Rod Prellwitz of Chen & Giger's stability number charts [ref ???]. A seepage correction factor may also be used in the critical height analysis. This factor also is based of curve fitting, this time of Figure 5a in R-1 Supplement No. 6 [ref ???].

Table 1 shows an example of the tabular results produced by a roadcut analysis, while Appendix 1 shows selected screen displays from a sample run.

S S I S C H

SLOPE STABILITY ANALYSIS BY INFINITE SLOPE AND CRITICAL HEIGHT

Level 2

SOIL DENSITY dry (pcf)	130.00	SOIL DENSITY sat (pcf)	140.00		
SOIL DEPTH (ft)	10.00	GROUNDWATER DEPTH (ft)	10.00	ROOT DEPTH (ft)	1.00
SOIL COHESION (psf)	40.00	ROOT COHESION (psf/ft)	20.00		
ANGLE INT. FRICT (deg)	35.00	GROUND SLOPE (deg)	30.00	PHREATIC SLOPE (deg)	30.00
CUT SLOPE (deg)	45.00	DITCH CUT SLOPE (deg)	18.40		
DITCH HEIGHT (ft)	0.00	DITCH WIDTH (ft)	0.00		
SEEPAGE CORRECTION	1.00	WATER HEIGHT ON CUT	21.87	ROCK HEIGHT ON CUT	1.79
CRITICAL HEIGHT (ft)	29.19	CUT HEIGHT, eff. (ft)	21.87	CUT HEIGHT, act. (ft)	21.87

CALCULATED FACTOR OF SAFETY = 1.72

S T A B L E

DATA REQUIREMENTS

I. STATION DATA

A chart ~~Listing~~ of the current value~~s~~ for each of the following data is ~~are~~ displayed, and the user is asked which values are to be modified. Those items marked with an asterisk (*) have values determined by the data stored for a level 1 landtype code, if one has been specified. Those parameters with ranges in level 1 use the average for level 2 values.

datum	unit
STATION IDENTIFICATION	40 characters
*SOIL DENSITY, DRY	pcf
*SOIL DENSITY, SATURATED	pcf
*SOIL DEPTH	ft
GROUNDWATER DEPTH	ft
ROOT DEPTH	ft
*SOIL COHESION	psf
*ROOT COHESION	psf
*SOIL ANGLE OF INTERNAL FRICTION	degrees
*GROUND SLOPE	degrees or %
PHREATIC SLOPE	degrees or %

Figure 1 shows a typical slope cross-section, with site parameters indicated.

II. ROADCUT ANALYSIS

The data specified for the most recent station data will be used (whether or not an infinite slope analysis has been requested) in addition to some data specific to the road template used. These new data are listed below.

Data Required for Full-bench Template

datum	unit
CUT SLOPE	degrees or ratio
ROAD WIDTH	ft
DITCH SLOPE	degrees or ~~units~~ ratio
DITCH DEPTH	ft
DITCH BOTTOM WIDTH	ft

Data Required for Self-balanced Template

datum	unit
CUT SLOPE	degrees or ratio
FILL SLOPE	degrees or ratio
ROAD WIDTH	ft
FILL DENSITY	pcf
ASSUMED FILL COMPACTION FACTOR	%
ASUMED PERCENT LOSS IN ROOT ZONE	%
DITCH SLOPE	degrees or ratio
DITCH DEPTH	ft
DITCH BOTTOM WIDTH	ft

Data Required for User-defined Geometry

datum	unit
CUT SLOPE	degrees or ratio
CUT HEIGHT	ft
HEIGHT OF GROUNDWATER ON CUT	ft
HEIGHT OF ROCK ON CUT	ft

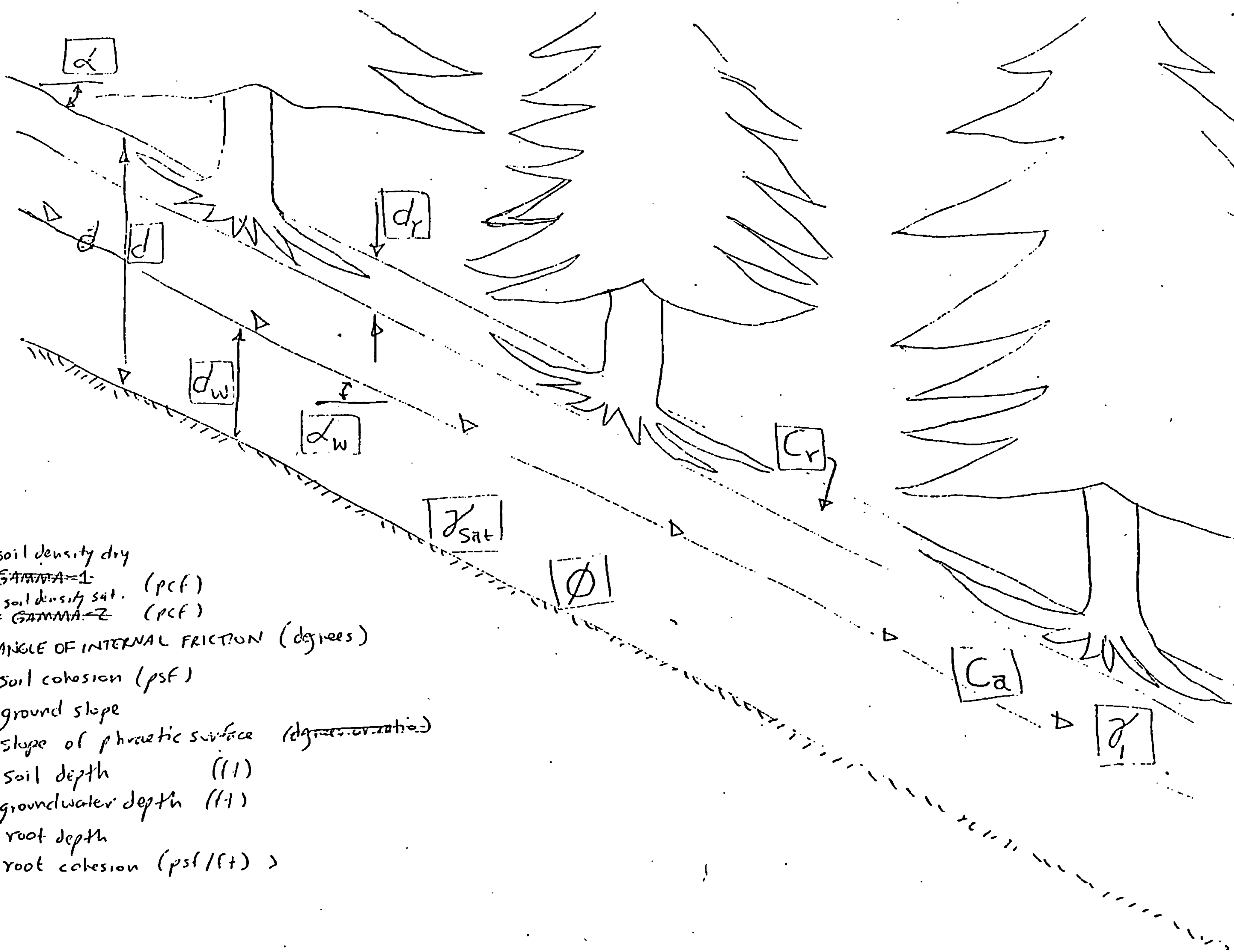
Figure 1 shows a cross-section depicting the data used in an infinite slope analysis, and as a base for the roadcut analyses. Figures 2 and 3 show example cross-sections for full-bench and self-balanced roadcuts.

LINKAGE TO LEVEL I

I. Level 1 to Level 2

SSISCH can read landtype code data from a level 1 SLIDES database and use values derived from them for most of the site data, as noted in the section above. You are asked whether you wish to use a level 1 database, and, if so, you are asked for the name of that file. A default file name has been included, and it can be changed upon transfer to your system. Once a filename has been specified, SSISCH attempts to read the file, and lists the available landtype codes and requests that you choose one. The data values associated with the chosen code are then displayed, and you are requested to verify whether or not the correct code has been specified. If not, you are allowed to try another. It is thus possible to snoop through the level 1 database.

INFINITE SLOPE ANALYSIS



γ_1 = ~~GAMMA-1~~ soil density dry (pcf)

γ_{sat} = ~~GAMMA-2~~ soil density sat. (pcf)

ϕ = ANGLE OF INTERNAL FRICTION (degrees)

C_a = soil cohesion (psf)

α = ground slope

α_w = slope of phreatic surface (~~degrees or ratio~~)

d = soil depth (ft)

d_w = groundwater depth (ft)

d_r = root depth

< C_r = root cohesion (psf/ft) >

FULL-BENCH TEMPLATE EXAMPLE

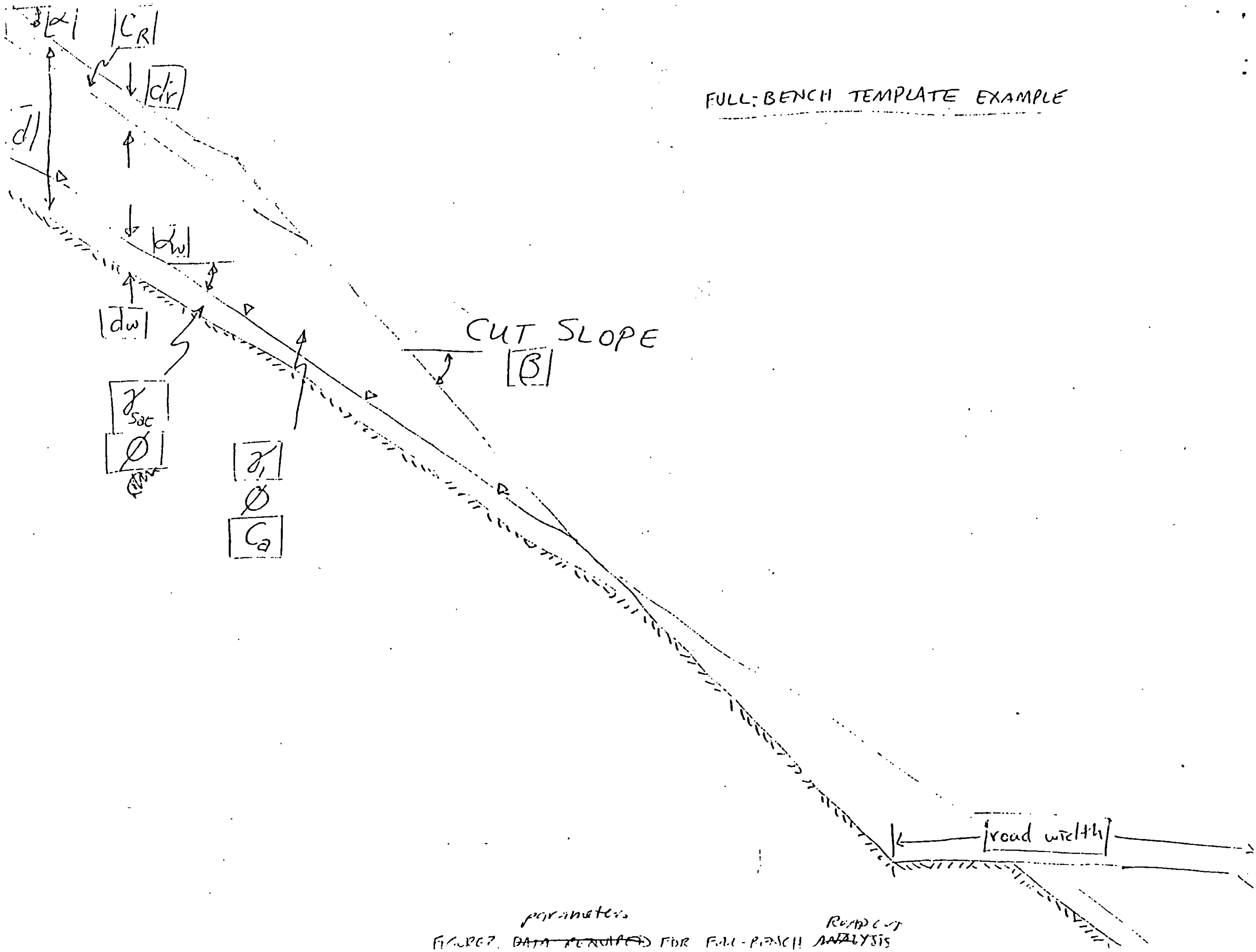
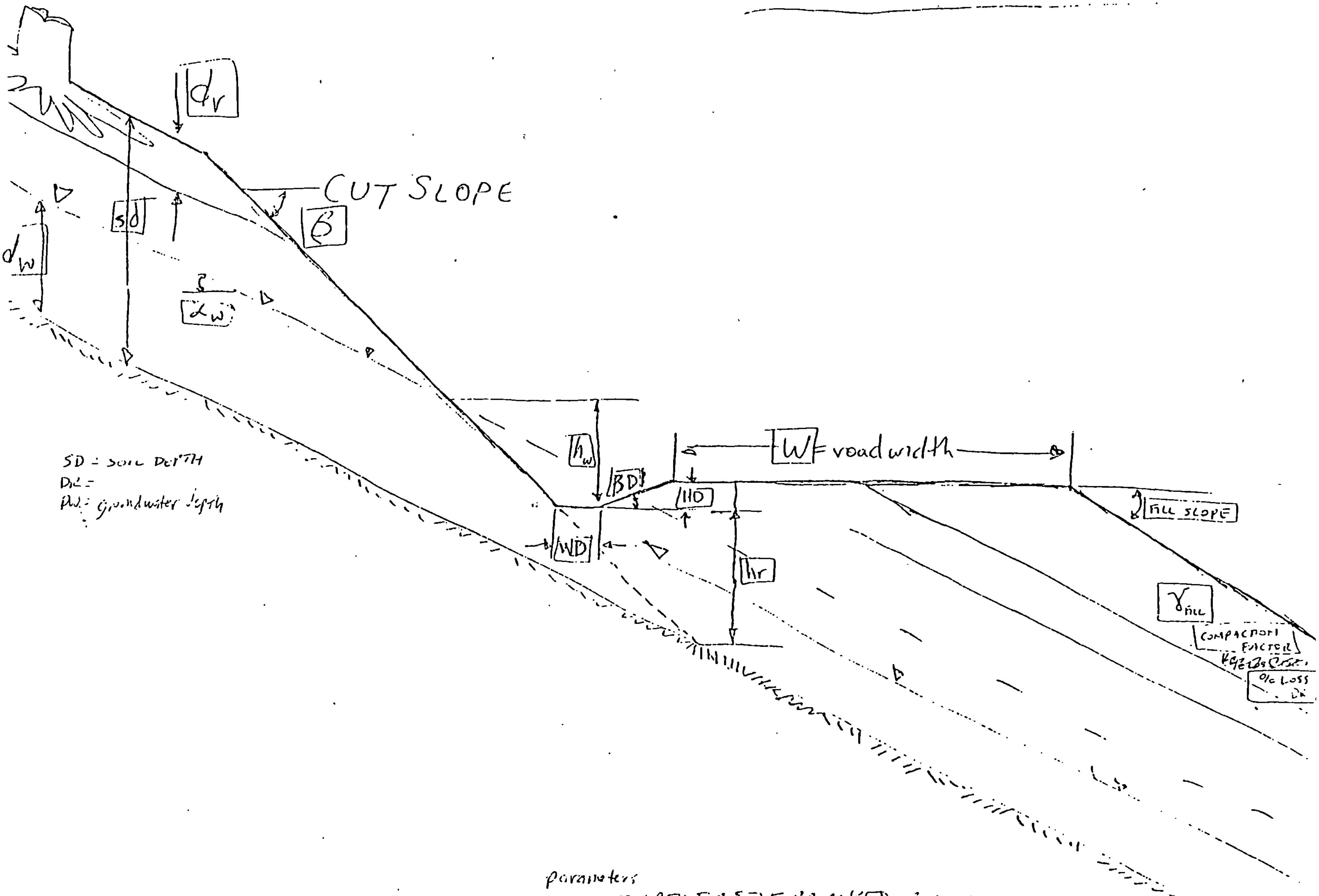


FIGURE 7. ~~DATA REQUIRED~~ parameters FOR FULL-BENCH Road cut ANALYSIS

SELF-BALANCE CROSS-SECTION



parameters

DATA REQUIRED FOR SELF-BALANCED ROAD

The following data are included in the level 1 SLIDES landtype code database:

LANDTYPE CODE	(0..8 characters)
SOIL DEPTH	ft
GROUND SLOPE	percent
SOIL COHESION minimum	psf
SOIL COHESION maximum	psf
ROOT STRENGTH minimum	psf/ft
ROOT STRENGTH maximum	psf/ft
SOIL ANGLE INT. FRICTION min.	degrees
SOIL ANGLE INT. FRICTION max.	degrees
SOIL DENSITY - DRY	pcf
SOIL DENSITY - SATURATED	pcf

All of these values may be used as preliminary level 2 site data. Soil cohesion, root strength, and soil angle of internal friction values used in the level 2 analysis are the arithmetic mean of the range specified for level 1. Once a level 1 code has been accepted, you are allowed to make any changes using the standard station data modification routine.

II. Level 2 to Level 1

This version of SSISCH does not yet implement a feedback routine from level 2 to the level 1 database. However, one is anticipated, and it is expected to work in the following way.

Any modifications made to the level 1 data accessed by SSISCH can optionally be written to the end of a disk file. Information entered in the file each time will include

LANDTYPE CODE (or more precicely, the position within the landtype code file which that landtype code holds),
the actual DATA VALUES used,
the NAME OF THE USER,
a SHORT EXPLANATION of the site and why the data should be included in the feedback process,
and any other PERTINENT INFORMATION, such as date, etc.

The actual updating of the level 1 database will <u>not</u> be done automatically. Each group of users will have to set up a set of guidelines for who is allowed to enter desired modifications in the feedback file, and who will have the ultimate say as to which modifications will actually be used in the feedback. In addition, all users will have to be forewarned of any changes in the level 1 datafiles.

The method of updating the level 1 database currently being researched is based upon a Bayesian model for updating an assumed uniform distribution to a pair of expected value - variance figures using the added knowledge of actual measured data values. These expected value - variance pairs will then have to be converted in some manner back to minimum - maximum pairs (i.e., an assumed uniform distribution) again to fit the needs of the level 1 analysis.

PROGRAM OPERATION

[HOW TO RUN IT]

[SEE APPENDIX FOR SAMPLE RUN]

ANALYSIS METHODS

I Factor of Safety

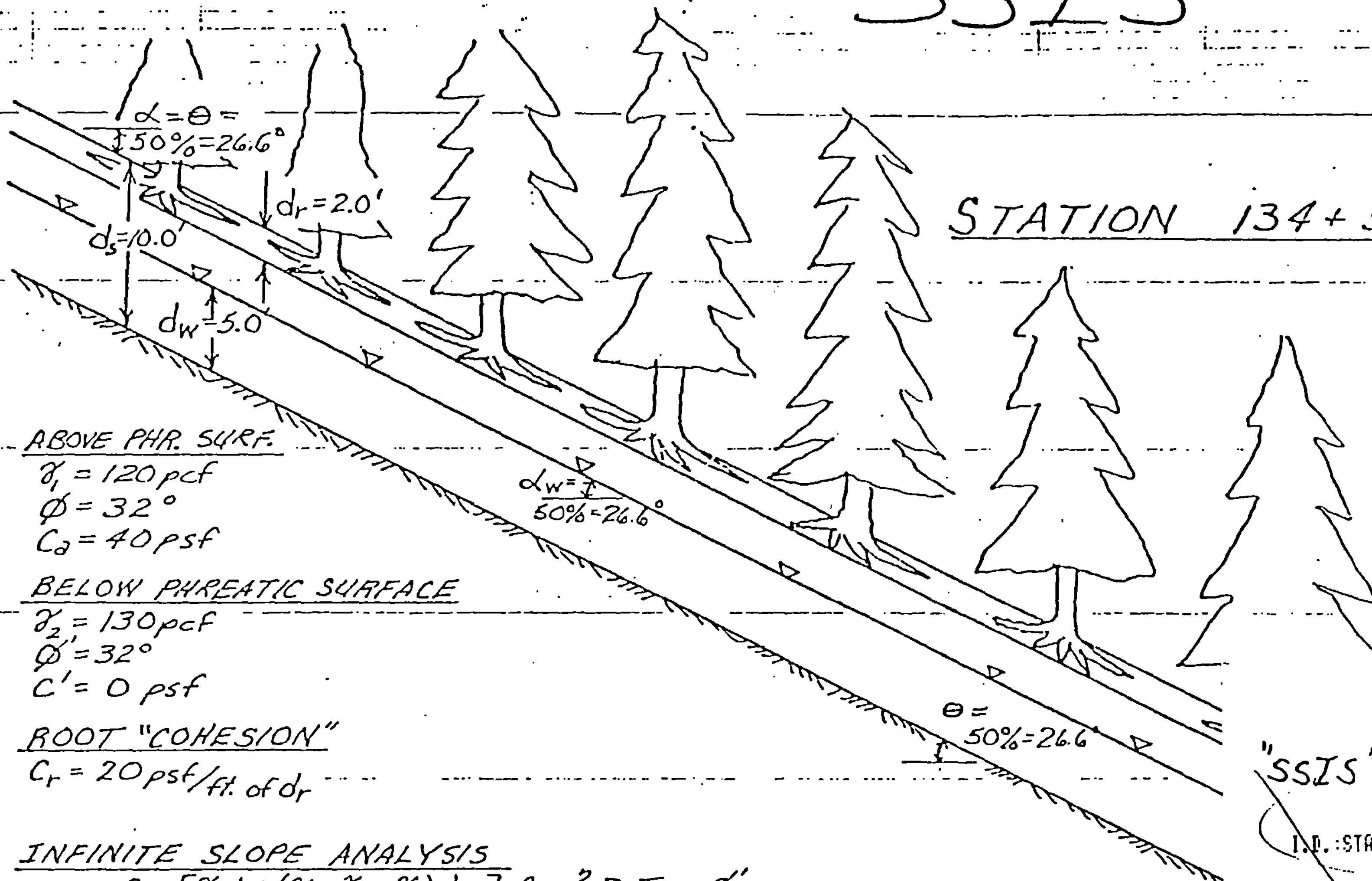
~~The formulas used in the factor of safety analysis are~~ Q-SLOPE ANALYSIS BASED ON FORMULAS given in Figure 4.

II Seepage -- curve fitting

III N -- curve fitting STABILITY NUMBER

"SSIS"

STATION 134+50



ABOVE PHR. SURF.

$\gamma_1 = 120$ pcf

$\phi = 32°$

$C_a = 40$ psf

BELOW PHREATIC SURFACE

$\gamma_2 = 130$ pcf

$\phi' = 32°$

$C' = 0$ psf

ROOT "COHESION"

$C_r = 20$ psf/ft. of d_r

INFINITE SLOPE ANALYSIS

$$F.S. = \frac{C + [\gamma_1 d + (\gamma_2 - \gamma_w - \gamma_1) d_w] \cos^2\theta \tan\phi'}{[\gamma_1 d + (\gamma_2 - \gamma_1) d_w] \cos\theta \sin\theta}$$

C ?

USE $C = C' + C_r d_r = 0 + 20 \times 2.0 = 40$ psf

$$F.S. = \frac{40 + [120 \times 10.0 + (130 - 62.4 - 120) \times 5.0] \times \cos^2(26.6°) \times \tan 32°}{[120 \times 10.0 + (130 - 120) \times 5.0] \times \cos 26.6° \times \sin 26.6°}$$

$$= \frac{508.6}{500.5}$$

F.S. = 1.02

"SSIS" SOLUTION:

I.D.:STATION 134+50

TRIAL 1

dr= 2.0 ft.
cr= 20.0 psf/ft.
Cs= 0.0 psf
coh.= 40.0 psf
den.= 120.0 pcf
sat. den.= 130.0 pcf
phi= 32.0 deg.
ds= 10.0 ft.
dw= 5.0 ft.
theta= 26.6 deg.
FS=unknown

FS= 1.02

4/4/83

PROGRAM SPECIFICATION

SSISCH can read most of its site data from a level 1 landtype code disk file, or all parameter values may be entered from the keyboard. Any values read from disk may also be modified from the keyboard before or after analysis. Roadcut data may be entered from the keyboard only at present, but the ability to read commonly used values from a disk file has been partially implemented.

Program output consists of several forms. First, output is sent to the video screen. This is the only form which output takes if only an infinite slope analysis is performed. If one or more roadcut analyses are performed, a plot of the site and roadcut cross-section may be displayed on the color graphics monitor, or it may be sent to the pen plotter. The plot's scale can be adjusted until the display is pleasing and fits nicely on the screen or paper. Also, a table of results, as shown in Table 1, may be sent to the printer.

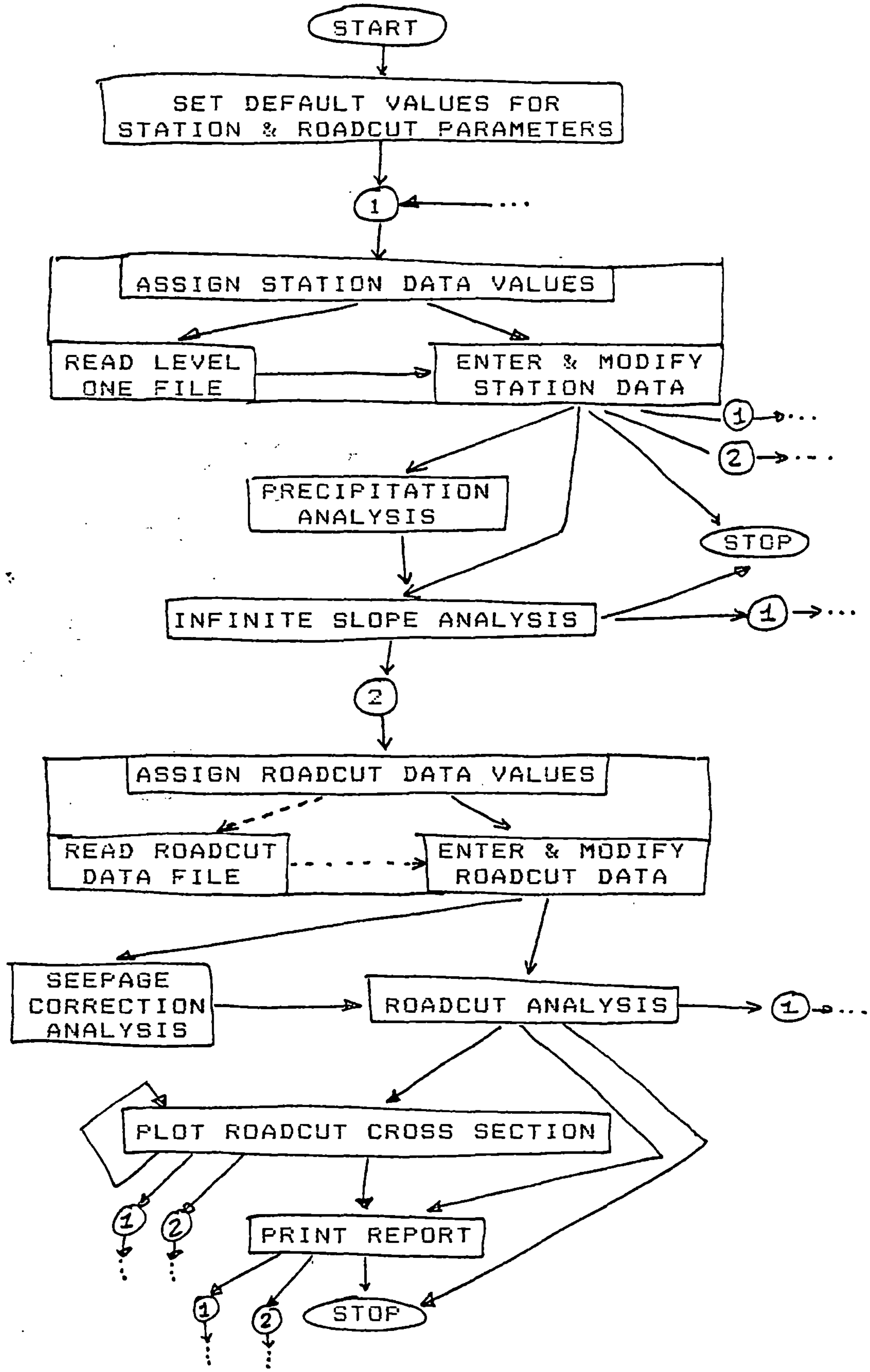
All plotting is done through calls to "turtle graphics" (actually polar coordinate) plotting subroutines. These routines will have to be modified slightly for varying plotting devices, and are described separately in the SSISCH Implementor's Guide.

SSISCH consists of a main program and twelve subprograms, not including the turtle graphics routines. The name and a short description of each subprogram follow. Each is described in more detail in the SSISCH Implementor's Guide.

MODSTA	--	Enter and modify existing station data
MODCUT	--	Enter and modify existing roadcut data
ISSTAB	--	Calculate slope stability by infinite slope
PRECIP	--	Dummy routine to hold a precipitation analysis to predict or model groundwater depth
SEEPGE	--	Calculate seepage factor, S
WTIDR	--	Calculate groundwater intercept height on cut
FULBEN	--	Calculate the roadcut dimensions for a full-bench road cross-section
SELBAL	--	Calculate the roadcut and fill dimensions for a self-balanced road cross-section.
PLOTRC	--	Plot roadcut cross-section
READL1	--	Read level 1 landtype code file data
DTOR	--	Function to convert degree to ratio measurement
RTOD	--	Function to convert ratio to degree measurement

An overview of SSISCH's flow of operation is given in Figure 5.

Figure 5. SSISCH FLOW DIAGRAM



APPENDIX - SAMPLE RUN

```
D:LEVEL2

Slope Stability Analysis by Infinite Slope and Critical Height

Do you want to read data from level I file? (Y/N) N

           STATION PARAMETER MODIFICATION

 < 1>    Station Identification
 Level 2
 < 2>    Soil density, dry                   120.00 pcf
 < 3>    Soil density, saturated             130.00 pcf
 < 4>    Soil depth                            6.00 feet
 < 5>    Groundwater depth                     2.00 feet
 < 6>    Root depth                            1.00 feet
 < 7>    Soil cohesion                        40.00 psf
 < 8>    Root cohesion                        20.00 psf/ft
 < 9>    Soil angle of internal friction      34.00 deg      67.45 %   <12>
 <10>    Ground slope                         30.00 deg      57.74 %   <13>
 <11>    Phreatic slope                       30.00 deg      57.74 %   <14>

 <15>    Go with these values
 < 0>    Redisplay screen

        Change which ? 6

Enter new Root depth             : 1.5

           STATION PARAMETER MODIFICATION

 < 1>    Station Identification
 Level 2
 < 2>    Soil density, dry                   120.00 pcf
 < 3>    Soil density, saturated             130.00 pcf
 < 4>    Soil depth                            6.00 feet
 < 5>    Groundwater depth                     2.00 feet
 < 6>    Root depth                            1.50 feet
 < 7>    Soil cohesion                        40.00 psf
 < 8>    Root cohesion                        20.00 psf/ft
 < 9>    Soil angle of internal friction      34.00 deg      67.45 %   <12>
 <10>    Ground slope                         30.00 deg      57.74 %   <13>
 <11>    Phreatic slope                       30.00 deg      57.74 %   <14>

 <15>    Go with these values
 < 0>    Redisplay screen

        Change which ? 15
```

```
DO YOU WISH TO PERFORM A ROAD ANALYSIS (Y/N)? Y

            ROADCUT PARAMETER MODIFICATION

  < 0>    Template : FULL

  < 1>    Cut slope                              45.00 deg       1.00:1   < 6>

  < 2>    Road width                             16.00 feet
  < 3>    Ditch depth                             0.00 feet
  < 4>    Ditch bottom width                      0.00 feet
  < 5>    Ditch slope                            18.40 deg       3.01:1   < 7>


  <16>    Values OK.

       Change which ? 0

Self-balanced, Full bench, or User-defined (S/F/U) ? S

            ROADCUT PARAMETER MODIFICATION

  < 0>    Template : SELF

  < 1>    Cut slope                              45.00 deg       1.00:1   < 6>

  < 2>    Road width                             16.00 feet
  < 3>    Ditch depth                             0.00 feet
  < 4>    Ditch bottom width                      0.00 feet
  < 5>    Ditch slope                            18.40 deg       3.01:1   < 7>

  < 8>    Fill slope                             45.00 deg       1.00:1   <12>
  < 9>    Assumed fill compaction                20.00
  <10>    Assumed % loss in root zone            15.00 %
  <11>    fill density                          100.00 pcf


  <16>    Values OK.

       Change which ? 0

Self-balanced, Full bench, or User-defined (S/F/U) ? U

            ROADCUT PARAMETER MODIFICATION

  < 0>    Template : USER

  < 1>    Cut slope                              45.00 deg       1.00:1   < 6>

  <13>    Cut height                             30.00 feet
  <14>    Groundwater height on cut              15.00 feet
  <15>    Road height on cut                    -10.00 feet
```

Do you want to use the PRECIPITATION ANALYSIS? (Y/N) N

Do you want to do an INFINITE SLOPE ANALYSIS? (Y/N) Y

FACTOR OF SAFETY = 1.06

S T A B L E

F.S. = 341.36 / 320.56

NEW STATION (Y/N)? N

Change which ? 0

Self-balanced, Full bench, or User-defined (S/F/U) ? F

ROADCUT PARAMETER MODIFICATION

< 0>	Template : FULL			
< 1>	Cut slope	45.00 deg	1.00:1	< 6>
< 2>	Road width	16.00 feet		
< 3>	Ditch depth	0.00 feet		
< 4>	Ditch bottom width	0.00 feet		
< 5>	Ditch slope	18.40 deg	3.01:1	< 7>

<16> Values OK.

Change which ? 16

CUT N = 54.75 HC = 20.90 H = 14.19
S T A B L E

PLOT ROAD CUT (Y/N) ? Y

Plot on Pen plotter or color Video monitor? (P/V) [V] V

SEND OUTPUT TO PRINTER (Y/N) ? N

NEW STATION (Y/N) ? N

DO YOU WISH TO PERFORM A ROAD ANALYSIS (Y/N)? N
STOP

Item 3

Review 11/7/84

SLIDES User's Manual

Version 1.00

January 1984

Level 1 landslide hazard mapping computer program
Infinite slope model

D E Hall & T R Howard
University of Idaho

Revised July 1984

CONTENTS

ABSTRACT

Land managers need a uniform and effective system for predicting landslide potential on forested slopes. No single geotechnical or statistical method is appropriate for all types of decisions. The Forest Service in cooperation with the University of Idaho is therefore developing a system suited to three levels of application:

Level I - Resource Allocation -- Provide managers with an overview of landslide potential adequate for developmental planning.

Level II - Project Planning -- Predict response of slide-prone areas to various harvesting systems & transportation routes.

Level III - Critical Site Stabilization -- Evaluate stabilization techniques at critical sites before and after construction.

The three levels are suited to the resource planner, road locator, and engineer, respectively.

SLIDES is a program which fits into the Level I category. Stability analysis delineates areas susceptible to landslides on a broad scale to alert the land manager to land units of greatest hazard intensity. [The number and magnitude of landslides resulting from resource development can be predicted through statistical correlation to a landslide inventory.]

PROGRAM OVERVIEW

SLIDES is a computer program which uses an infinite slope model to evaluate an area's susceptibility to landslide. This susceptibility is measured by two standard figures: factor of safety and probability of failure. The infinite slope equations used in SLIDES are modifications of those used by Simons, Li and Ward in their LSMAP program. Version 1.00 of SLIDES runs on a microcomputer running FORTRAN IV in an interactive environment. Details about the hardware and operating environment used are given in appendix 3.

The SLIDES program is intended to give the user a broad overview of an area showing the regions which are deemed to have a high probability of failure due to landslide. These areas could then be studied in more detail with a "level 2" analysis.

SLIDES analyzes landtype polygons as opposed to a grid of landtype codes. "Polygons" are irregularly shaped homogeneous areas on a map. Two types of information are needed as input for each polygon. The first is an identifying integer that corresponds to the landtype that the polygon outlines. The second type of information consists of the X-Y coordinates of each polygonal outline. [- from Computers & Geosciences, V8 #2, 1982, p.149.]

Table 1 lists the data that must be supplied for each landtype. Admittedly, some of these factors have yet to be correlated to the landtype codes presently in use, so "best guesses" must be used. In addition, provision has been built into SLIDES to specify the relative groundwater saturation level for each landtype code by means of a subroutine call. When predictive groundwater models are available, they may be plugged into the existing framework.

Table 1. Landtype code data

soil depth (feet)
depth to groundwater (feet); optional
slope (percent)
soil cohesion (maximum and minimum ; psf)
root cohesion (maximum and minimum; psf/ft)
soil angle of internal friction (max and min; degrees)
soil density - sat (pcf); optional
soil density - dry (pcf); optional

The polygon number, landtype code, polygon location, and calculated factor of safety & probability of failure are printed for each polygon within the specified area of interest. The polygons can also be plotted on a graphics screen with each polygon numbered, or on paper using a pen plotter, with factor of safety figures plotted in each.

THEORY OF OPERATION

[from SIMONS LI & WARD report MAPPING OF POTENTIAL LANDSLIDE AREAS IN TERMS OF SLOPE STABILITY ... modified]

The analysis done by this program is applicable to slide and flow type landslides. Rock masses are a more complex problem because of their dependence on the geometry of failure planes.

Various types of slope stability models exist. The two basic types are infinite slope and finite slope models, each with its own set of assumptions. Common to both types is the method of formulation into a factor of safety equation. In the factor of safety equation a ratio of resisting to driving forces is formed. Resistive forces are related to soil strength and vegeative parameters while the primary driving force is the downslope weight of the soil mass. If resistance is less than the driving force then the factor of safety is less than one, indicating failure. The infinite slope model is applicable primarily to failure occurring along planar surfaces.

The model used in SLIDES represents the consolidation and refinement of ideas presented by Swanson, et al; O'Laughlin; Brown & Sheu; and Simons, Ward, & Li. The Factor of Safety analysis is based upon the following equation:

$$FS = \frac{\dfrac{2\,(Cs + Cr)}{\gamma w H \sin 2\beta} + \left[\dfrac{qo}{\gamma w H} + \left(\dfrac{\gamma sat}{\gamma w} - 1\right)M + \dfrac{\gamma}{\gamma w}(1-M)\right]\dfrac{\tan \phi}{\tan B}}{\dfrac{qo}{\gamma w H} + \left(\dfrac{\gamma sat}{\gamma w}\right)M + \dfrac{\gamma}{\gamma w}(1-M)} \qquad (1)$$

where:
- Cs is soil cohesion, expressed as a pressure
- Cr is effective root cohesion, expressed as a pressure
- γw is unit weight of water
- H is a soil depth measure equal to d / cos B
- d is soil depth
- B is slope inclination
- qo is tree surcharge expressed as a pressure
- γsat is saturated unit weight of soil
- γ is unit weight of the soil
- M is relative groundwater height
- ϕ is angle of internal friction for soil

This equation defines the landslide potential of a slope in terms of factor of safety value. Relative error in factor of safety values can be approximately 20 to 30 percent [Ward, 1976]. For relative rankings of hazards, limits of factor of safety values can be established. A realistic set of relative hazard levels is:

1) High potential for	$FS < 1.2$
2) Medium potential for	$1.2 \leq FS \leq 1.7$
3) Low potential for	$1.7 < FS$

Equations used for determining landslide probability are derived from Equation 1. The average factor of safety, $\underline{FS}$, is:

$$\underline{FS} = L1\ (\underline{Cs} + \underline{Cr}) + L2\ (\underline{\tan \emptyset}) \tag{2}$$

The variance of the factor of safety, Var[FS], is

$$\begin{aligned} Var[FS] = {} & L1^2\{Var[Cs] + \underline{Cs}^2 + 2\underline{Cs}\ \underline{Cr} + Var[Cr] + \underline{Cr}^2\} \\ & + L2^2(Var[\tan \emptyset] + (\underline{\tan \emptyset})^2) \\ & + 2\ L1\ L2\ (\underline{\tan \emptyset})\ (\underline{Cs} + \underline{Cr}) - \underline{FS}^2 \end{aligned} \tag{3}$$

The constants L1 and L2 are defined as follows:

$$L1 = \frac{2}{\gamma_w H \sin(2\beta)\ [\frac{qo}{\gamma_w H} + \frac{\gamma_{sat}}{\gamma_w} M + \frac{\gamma}{\gamma_w}(1-M)]}$$

$$L2 = \frac{\left[\frac{q_o}{\gamma_w H} + \left(\frac{\gamma_{SAT}}{\gamma_w} - 1\right)M + \frac{\gamma}{\gamma_w}(1-M)\right]}{\left[\frac{q_o}{H} + \left(\frac{\gamma_{SAT}}{\gamma_w}\right)M + \frac{\gamma}{\gamma_w}(1-M)\right] \tan\beta}$$

SW&Li's program, however, uses

$$L2 = \frac{\left[\frac{q_o}{\gamma_w H} + \left(\frac{\gamma_{SAT}}{\gamma_w}\right)(M) + \frac{\gamma}{\gamma_w}(1-M)\right] - M}{\left[\frac{q_o}{\gamma_w H} + \left(\frac{\gamma_{SAT}}{\gamma_w}\right)(M) + \frac{\gamma}{\gamma_w}(1-M)\right] \text{TAN}(\beta)}$$

Develop optional subroutine, route for Groundwater as a variable input (each unit to develop equation for groundwater rise as a function of precipitation, if this data is available).

The mean and variance computed from Equations 2 and 3 can be used to estimate failure probability. This is written as

$$P[FS \leq 1] = p$$

where p is the probability of failure and $P[FS \leq 1]$ is the cumulative probability that FS is less than or equal to one. A reasonable distribution of failure probabilities is a normal or Gaussian distribution. Making this choice allows computation of the failure probability.

First, a non-dimensional variate, U, is computed as

$$U = \frac{1 - \underline{FS}}{(Var[FS])^{1/2}}$$

The value of U is then used to compute another variable, p, the cumulative failure, as

$$p = 0.4 / |u| \qquad if\ |u| \leq 0.13$$

or

$$p = -0.01314 + 0.49494\,|u| - 0.15804\,|u|^2 + 0.01661\,|u|^3 \qquad if\ |u| > 0.13$$

From U and p the failure probability is found as:

$P[FS \leq 1] = p$ if $U>0$
$P[FS \leq 1] = 1-p$ if $U<0$
$P[FS \leq 1] = 0.5$ if $U=0$

As with potential rankings, probabilities can be grouped into three hazard classes:

1) High probability for $60\% < P[FS \leq 1]$
2) Medium probability for $30\% \leq P[FS \leq 1] \leq 60\%$
3) Low probability for $P[FS \leq 1] < 30\%$

Again, these limits are arbitrary.

The means and variances of Cs, Cr, and tan Ø must be known or estimated in order to find the failure probability. Ward, Li and Simons assumed ~~that~~ these variables to be uniformly distributed random variables. With this assumption, the mean and variance of a random number are

$$\underline{X} = (Xa + Xb) / 2 \quad \text{and} \quad Var[X] = (Xb - Xa)^2 / 12$$

where Xa and Xb are lower and upper limits on the variable X.

We assumed that Cs, Cr, and Ø (<u>not</u> tan Ø) were uniformly distributed. This assumption yields a different equation for the {expected value ("mean")} variance of tan Ø as follows:

$$\cancel{\underline{TAN\phi}\ (= E[TAN\phi]) = \ln(CPHI)/(PHI2 - PHI1)}$$

$$\cancel{\text{where } CPHI = \cos(PHI1)/\cos(PHI2)}$$

$$E[TAN\phi] = \frac{1}{\phi_2 - \phi_1} \ln\left(\frac{\cos\phi_1}{\cos\phi_2}\right)$$

$$VAR[TAN\phi] = \frac{1}{\phi_2 - \phi_1}(\tan\phi_2 - \tan\phi_1) - (E[TAN\phi])^2 - 1$$

DATA REQUIREMENTS

Two data sets are required by SLIDES: landtype codes and associated data, and polygon data. You will have many polygon data files to cover a large area or disparate small areas, but probably only one landtype code file. Each of these data sets is described below. The physical format of the files is described in the SLIDES Implementor's Manual.

Landtype Code File

The first data set contains the landtype codes used and the values to be used for each for the data listed in Table 1. A short description of each code may also be given. Eight characters are available for the landtype names. The scheme used to name landtypes is of no real significance to SLIDES; only the order in which they are entered into the Landtype Code File is important. The polygons are linked to their proper landtypes through the position of the landtype code in the Landtype Code File. This data file may also be accessed by the level two program, SSISCH.

This file is not limited to use by a particular Polygon Data File. In fact, there will probably be one Landtype Code File for a whole forest system, while there will be many Polygon Data Files referring to it.

The following data are specified for each landtype code in the Landtype Code File:

soil depth (feet)
depth to groundwater (feet); optional
slope (percent)
soil cohesion (maximum and minimum ; psf)
root cohesion (maximum and minimum; psf/ft)
soil angle of internal fricion (max and min; degrees)
soil density - sat (pcf); optional
soil density - dry (pcf); optional

As noted, three of these values are optional. A blank or zero in the soil density fields indicate a missing value. If either soil density is missing, then both are calculated. A missing value for depth to groundwater is indicated by a negative value. If missing, the groundwater subroutine is invoked to determine a relative saturation by groundwater.

Landtype Code Files use a filename extension of ".LTC" (standing for LandType Code).

Print headings w/ output of file

Polygon Data File

The second type of data file contains cartesian coordinates describing the boundaries of "homogeneous" landtype regions in an area to be analyzed. In addition to these boundary coordinates, the coordinates of an "annotation point" are given. This point is used for a variety of things, as follows.

1. The coordinates of the interior point are used to determine whether the polygon is within the area to be analyzed as specified by the user.
2. The polygon number or factor of safety figure is printed at this point.
3. These coordinates are listed in the printed report, along with the polygon number, landtype code, and calculated factor of safety and probability of failure, to aid in locating the polygon.

Finally, a short description of the area covered is allowed, and the boundaries of the area are given, both in inches on the base map and in world coordinates. The origin used in digitizing is not restricted to any particular location.

A rectangular subsection of the area covered by the polygon data file may be analyzed by specifying the desired northern, southern, eastern and western boundary limits to be observed. These limits may be given in map inches or in world coordinates. Only those polygons whose annotation points fall within the specified limits are analyzed and plotted.

Polygon Data Files use a filename extension of ".VTX" (standing for VerTeX).

Limitations

The entire landtype code file (except the short description of each code) is read from disk once, and is stored in internal memory. A maximum of 99 codes is currently supported.

Data for a whole polygon are stored in internal memory at one time. A maximum of 100 vertices per polygon is supported. This includes the annotation point.

SLIDES imposes no restriction on the number of polygons described in a particular polygon data file, but there is a practical limit. Just what this limit is depends upon various factors. The primary reasons to restrict the number of polygons in a file are available disk space (on some systems), and, of greater importance in most cases, the time required to search through a large file from stem to stern to find all of the polygons that are located within a relatively small area of interest. On the other hand, if an area is fragmented into numerous polygon data files, you are eventually bound to have an area of interest which spans two or more files, and you'll have to work in pieces.

RUNNING SLIDES

These directions are specific to the Cromemco computer installation, but other installations can be expected to have similar operating procedures.

SLIDES is quite easy to use once the data files have been created. The Cromemco must be booted under the graphics operating system disk. A disk with both the Polygon Data File and the Landtype Code File must be present on a disk in drive B, and the SLIDES program must be available on some active drive.

Invoke the program by typing the program name, SLIDES. The screen will be cleared, and you will be asked a few questions. The program first asks you whether output is to be plotted on the color monitor, pen plotter, or not at all. Then, it asks for the names of the data files that it is to use. It then reports the area covered by the Polygon Data File, and asks what portion is to be analyzed.

These steps are listed below.

- Boot up under 48K graphics CDOS.
- Turn on the printer.
- Turn on the color graphics monitor.
- Place disk with data files to be used in drive B.
- Place disk with SLIDES program in an unused drive.
- Invoke program by typing SLIDES (preceeded by drive specifier, if required).

You will be asked for the following information:

Please enter the POLYGON data file name :

Enter the file name of the Polygon Data File which you wish to use. It must be present on the disk in drive B. Don't include the drive specifier or the ".VTX" extension.

Please enter the CODE data file name :

Enter the name of the Landtype Code File which you wish to use. It must be present on the disk in drive B. Don't include the drive specifier or the ".LTC" extension.

Send output to Video screen or Plotter? (P!V) [V]

Type a "P" to have polygons plotted on pen plotter or a "V" to have them plotted on the color graphics monitor. Default: Video.

Send output to printer? (Y!N) [N]

If you enter a reply of "Y" to this question, SLIDES will print a report listing, for each polygon analyzed, the polygon number (a sequential numbering within the polygon data file), the coordinates of the annotation point, the calculated factor of safety and probability of failure, and the landtype code. Default: No report.

SLIDES will print the header from the Polygon Data File, and you can verify that you are using the proper data. It will also list the northern, southern, eastern and western boundaries of the area covered by the data in the file in two sets of units. One is the actual units as digitized (generally inches on the base map). The other (theoretically) is some sort of world coordinate system, such as latitude/longitude in decimal form.

- You are asked to "DELIMIT AREA OF INTEREST"
  You may:
  - use the whole file
  - specify new boundaries in map inches
  - specify new boundaries in world coordinates

  Only those polygons whose annotation points are within the specified boundaries will be analyzed, and only those polygons which are analyzed are plotted. Any portions of polygons outside the user-specified boundaries are clipped. The resulting plot will be scaled to fit the color graphics screen or paper size of the pen plotter. Future versions of SLIDES are expected to adhere to a user-specified plot scale for the hard-copy plot.

- That's it. SLIDES will analyze and plot the polygons (in the order in which they are present in the Polygon Data File) and, if requested, print the results in tabular form. A PROCESSING COMPLETE message will great you when all has been accomplished successfully.

PROGRAM OUTPUT

1. Plot of polygons on color monitor, with polygon number, scaled to fill monitor.

2. With appropriate firmware, the polygon numbers may be deleted, and the polygons may be filled with the appropriate color or shading pattern to represent levels of factor of safety or probability of failure.

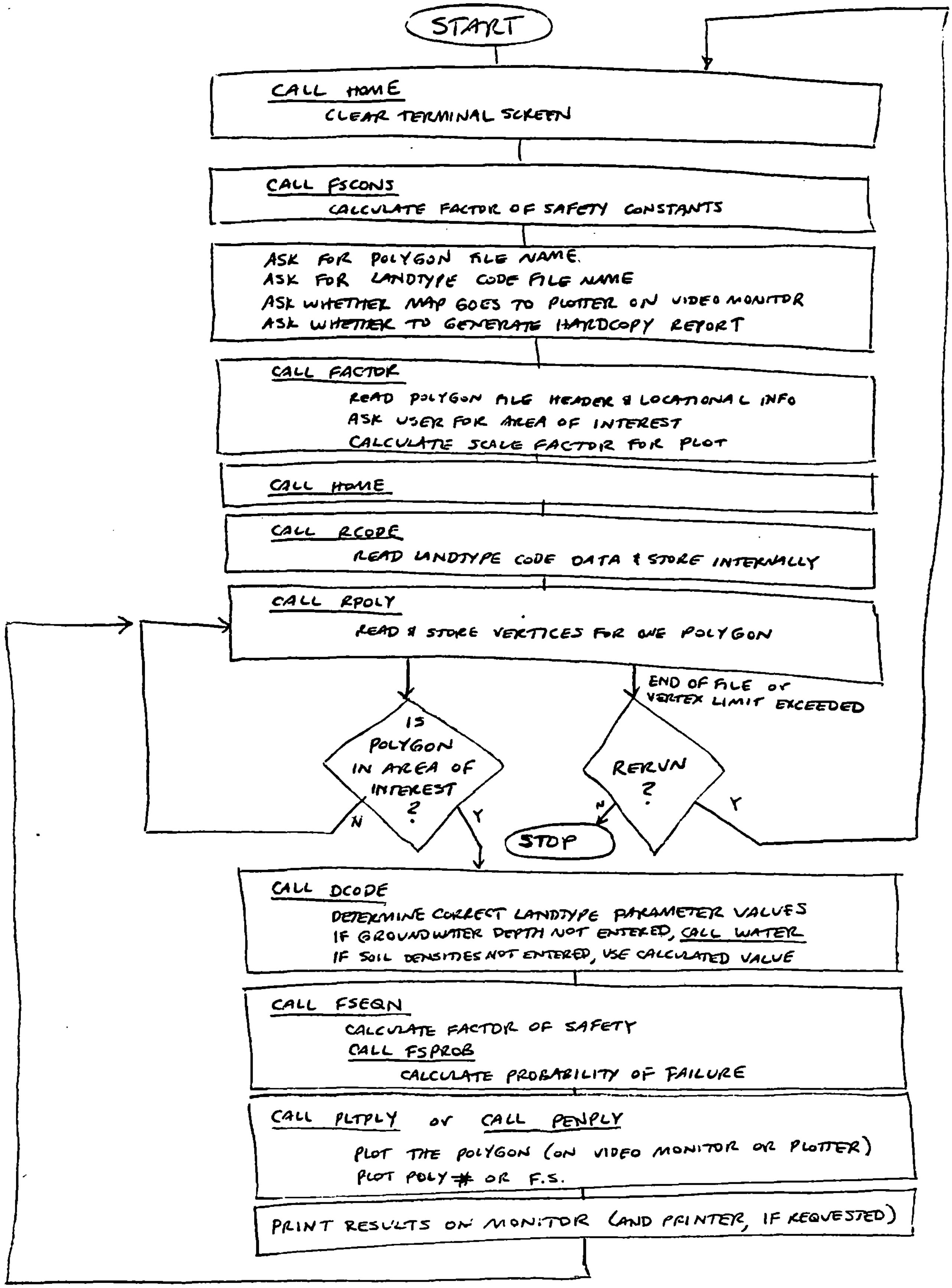
3. Plot of polygons, with the calculated factor of safety figure plotted in each, created by pen plotter. This would also be much more effective with polygon shading in different colors or densities.

4. List of polygon numbers, with associated landtype code, annotation point coordinates (in units in which they were digitized), and calculated factor of safety and probability of failure for each.

5. A separate but compatible program will plot on a pen plotter a base map showing polygon boundaries of a portion of a Polygon Data File. This base map will be at a user-specified scale. We expect to have an option in this program which will allow the user to mark sites to be analyzed through the level two program.

<u>OVERVIEW OF PROGRAM LOGIC</u>

OVERVIEW OF PROGRAM LOGIC
SLIDES



APPENDIX 1

SAMPLE DATA FILES & REPORTS

RESOURCE PLANNER'S DATA

	(DEPTH TO) d_w	d	SLOPE θ (% SLOPE)	γ (pcf must)	ϕ	C (psf)	C_R (psf)
				110	32°	80	0-40
22-3A	5-10	2-10	45-60%				0-40
64-2A	5-10	25-40	0-10%	120	34	50	0-60
64-2C	2-5	25-40	0-10%				0-60
66-1A	0-2	25-40	0-10%	85	20	200	40-125
71-1A	0-15	25-40	0-30%				20-80
71-1D	10-20	25-40	0-30%				tr
82-2B	5-10	5-10	10-20%				40-125
84-1A	2-10	5-10	10-45%	100	30°	100	0-40
85-2A	5-10	2-10	45-60%				20-80
85-2B	5-10	2-10	45-60%				tr
86-2A	5-10	2-10	10-45%	90	25°	200	0-40
86-2C	5-15	5-15	10-45%				20-80
86-2D	5-15	5-15	10-45%				0-40
87-2A	5-10	2-10	45-60%				20-80
87-2B	5-10	2-10	45-60%				0-40
87-2C	5-10	2-10	45-60%				40-125
87-2D	5-10	2-10	45-60%				
							0-40
64-2A	5-10	25-40	0-10%				0-60
64-2C	2-5	25-40	0-10%				20-80
71-1D	10-20	25-40	0-30%				0-60
84-2B	5-10	2-10	10-20%				0-40
85-3A	5-15	5-15	45-60%	110	30°	100	20-80
85-3B	↓	↓	↓				20-80
86-3B	5-15	5-15	10-20%				0-40
86-3C	5-15	5-15	10-45%				40-125
87-2D	5-10	2-10	45-60%				0-60
91-2B	3-8	5-40	10-45%				

SAMPLE LANDTYPE CODE FILE

GALMOD2 .LTC

landtype code	soil depth (ft)	depth to groundwater (ft)	surface slope (%)	soil cohesion, min (psf)	soil cohesion, max (psf)	root cohesion, min (psf)	root cohesion, max (psf)	ϕ_1, min (degrees)	ϕ_2 max, (degrees)	γ_{SAT} (pcf)	γ_{soil} (pcf)	unused
22-3A	6.	5.	60.	78.	82.	0.	40.	28.	36.	110.	90.	1
64-2A	33.	5.	10.	48.	52.	0.	40.	30.	38.	120.	100.	2
64-2C	33.	2.	10.	48.	52.	0.	60.	30.	38.	120.	100.	2
66-1A	33.	0.	10.	48.	52.	0.	60.	30.	38.	120.	100.	2
71-1A	33.	0.	30.	190.	210.	40.	125.	16.	24.	85.	65.	3
71-1D	33.	10.	30.	190.	210.	20.	80.	16.	24.	85.	65.	3
82-2B	8.	5.	20.	190.	210.	20.	80.	21.	29.	90.	70.	4
84-1A	8.	2.	45.	190.	210.	40.	125.	21.	29.	90.	70.	4
85-2A	6.	5.	60.	90.	110.	0.	40.	26.	34.	100.	90.	5
85-2B	6.	5.	60.	90.	110.	20.	80.	26.	34.	100.	90.	5
86-2A	6.	5.	45.	190.	210.	20.	80.	21.	29.	90.	70.	4
86-2C	10.	5.	45.	190.	210.	0.	40.	21.	29.	90.	70.	4
86-2D	10.	5.	45.	190.	210.	20.	80.	21.	29.	90.	70.	4
87-2A	6.	5.	60.	190.	210.	0.	40.	21.	29.	90.	70.	4
87-2B	6.	5.	60.	190.	210.	20.	80.	21.	29.	90.	70.	4
87-2C	6.	5.	60.	190.	210.	0.	40.	21.	29.	90.	70.	4
87-2D	6.	5.	60.	190.	210.	40.	125.	21.	29.	90.	70.	4
64-2A	33.	5.	10.	48.	52.	0.	40.	30.	38.	120.	100.	2
68-2C	33.	2.	10.	48.	52.	0.	60.	30.	38.	120.	100.	2
71-1D	33.	10.	30.	190.	210.	20.	80.	16.	24.	85.	65.	3
84-2D	6.	5.	20.	90.	110.	0.	60.	26.	34.	110.	90.	6
85-3A	10.	5.	60.	90.	110.	0.	40.	26.	34.	110.	90.	6
85-3D	10.	5.	60.	90.	110.	20.	80.	26.	34.	110.	90.	6
86-3B	10.	5.	20.	90.	110.	20.	80.	26.	34.	110.	90.	6
86-3C	10.	5.	45.	90.	110.	0.	40.	26.	34.	110.	90.	6
87-2D	6.	5.	60.	190.	210.	40.	125.	21.	29.	90.	70.	4
91-2B	33.	3.	45.	190.	210.	0.	60.	21.	29.	90.	70.	4

CALAREA1.DAT   SAMPLE POLYGON FILE (#1)

```
STUDY AREA 1 CALLATIN LANDSLIDE PROJECT
     19.52       4.36      19.59       6.28
    200.00       0.00     200.00       0.00
 13   8.06 10.90   6.47 13.79   6.47 13.28   6.36 13.02   6.62 11.07   7.03 11.28
      8.16 10.16   8.55 10.07   8.83 10.06   9.07 10.33   8.73 10.82   8.75 11.32
      8.38 11.95   8.22 11.60   7.98 11.64   7.64 11.44   7.67 11.34   7.54 11.51
      7.03 12.25   7.03 13.25   6.47 13.79
  6   9.02 10.02   9.06 10.30   8.82 10.05   9.40  9.67   9.31 10.09   9.36 10.40
      9.30 10.40   9.06 10.30
 12   9.82  8.85   8.55 10.06   9.31  9.52   9.79  8.67 10.49   7.51 11.24   6.80
     11.23  7.11 11.02  7.25 10.82  7.58 10.41  7.96 10.13   8.44  9.97   8.94
      9.79  9.45   9.39  9.68   8.82 10.07   8.82 10.06   8.55 10.06
 15   9.14 11.39   9.04 15.23   8.98 14.69   8.71 14.31   8.59 13.68   8.48 13.40
      8.34 11.93   8.75 11.29   8.74 10.00   9.08 10.31   9.37 10.40   9.25 10.10
      9.40  9.60   9.77  9.45   9.96  8.93 10.15   8.44 10.41   7.96 10.73   7.64
     11.00  7.24 11.25  7.09 11.25   6.81 11.58   6.62 11.74   6.84 11.86   7.06
     11.84  7.37 11.48  8.26 10.86   9.12 10.84   9.35 11.14   9.69 10.88   9.97
     10.70 10.84 10.43 10.95 10.29 11.58   9.78 12.32   9.55 12.61   9.69 12.74
      9.43 13.16   9.21 14.07   9.36 14.71   9.35 14.74   9.04 15.23
 10   7.47 13.88   6.46 14.91   6.47 13.73   7.04 13.25   7.54 11.50   7.67 11.34
      7.85 11.45   8.00 11.66   8.22 11.57   8.39 11.93   8.45 13.37   8.60 13.67
      8.73 14.31   8.98 14.70   9.03 15.23   9.02 15.37   8.83 15.36   8.51 15.40
      8.31 15.35   7.68 15.65   7.65 15.48   7.59 14.59   7.43 14.95   7.28 14.62
      7.23 14.87   6.88 15.02   6.88 15.02   6.46 14.91
 13  11.89  6.40 11.86  7.37 11.85  7.06 11.71  6.83 11.56  6.60 11.86  5.97
     12.07  5.99 12.12  5.70 12.26  5.47 12.60  5.75 12.68  6.07 12.66  6.57
     12.44  7.39 12.25  7.36 12.30  6.73 12.14  7.05 11.95  7.33 11.88  7.37

  1  13.96  5.40 12.56  6.66 12.71  6.12 12.56  5.74 12.25  5.49 12.40  5.06
     13.22  5.39 13.91  5.24 14.56  4.94 15.05  4.81 15.29  4.94 15.17  5.11
     14.95  5.12 14.44  5.51 13.71  5.60 13.14  5.58 12.79  5.51 12.72  5.72
     12.92  5.99 12.84  6.47 12.66  6.66
 17  11.71  8.35 10.31 11.57 10.45 10.98 10.68 10.83 10.87  9.95 11.16  9.68
     10.86  9.35 10.86  9.10 11.47  8.25 11.83  7.33 12.15  7.07 12.35  6.74
     12.27  7.36 12.43  7.38 12.64  6.66 12.84  6.47 13.32  7.08 13.02  7.60
     12.78  7.66 12.62  8.59 12.34  8.73 12.14  9.14 11.56  9.72 11.50  9.43
     11.56  9.11 11.36  9.31 11.39  9.82 11.33 10.02 11.15 10.14 11.35 10.24
     11.12 10.55 11.09 10.81 10.88 11.19 10.48 11.50 10.48 11.50 10.31 11.57

 18  11.78 11.75 11.66 11.34 11.36 11.25 11.05 10.75 11.11 10.52 11.35 10.21
     11.57 10.85 11.96 11.10 11.91 11.52 11.91 11.52 11.66 11.34
 13  10.56 12.14   9.35 14.73   9.21 14.07   9.43 13.13   9.69 12.76   9.55 12.60
      9.80 12.31 10.31 11.57 10.48 11.53 10.74 11.63 11.17 11.74 11.51 11.74
     11.08 12.15 11.51 13.15 11.42 13.65 10.66 13.86 10.61 12.94 10.53 12.67
     10.38 12.40 10.30 12.49 10.09 12.41 10.20 12.71 10.15 12.86   9.93 12.84
     10.11 13.10 10.22 13.73   9.97 14.42   9.35 14.73
  3   7.36 15.03   7.64 15.51   7.34 15.19   6.88 15.03   7.21 14.86   7.28 14.62
      7.41 14.93   7.61 14.63   7.64 15.51
 14   6.60 15.06   6.46 15.22   6.45 14.91   6.87 15.02   7.33 15.17   7.64 15.52
      7.67 15.67   7.67 15.80   7.53 15.92   7.40 15.52   6.92 15.19   6.89 15.19
      6.46 15.22
  7   6.65 15.43   6.45 15.71   6.46 15.22   6.91 15.22   7.38 15.51   7.55 15.92
      7.43 16.12   7.38 16.44   7.27 16.14   7.07 16.08   6.94 15.92   6.66 15.86
      6.45 15.71
```

5	6.56	15.96	6.45	16.67	6.44	15.71	6.66	15.85	6.95	15.93	7.06	16.07
	7.29	16.10	7.36	16.44	7.12	16.52	6.97	16.27	6.74	16.03	6.69	16.35
	6.99	16.78	6.69	16.90	6.45	16.67						
7	6.54	16.91	6.45	17.23	6.46	16.67	6.68	16.90	6.98	16.76	6.67	16.55
	6.73	16.03	6.96	16.29	7.12	16.52	7.38	16.43	7.16	16.66	6.92	17.14
	6.92	17.11	6.45	17.23								
3	6.55	17.39	6.46	17.67	6.44	17.20	6.94	17.14	7.18	16.61	7.37	16.45
	7.26	16.96	7.10	17.18	6.96	17.26	6.74	17.35	6.46	17.57		
3	7.60	15.88	7.39	16.45	7.44	16.12	7.53	15.90	7.68	15.78	7.67	15.34
	8.32	15.38	8.51	15.43	8.45	15.57	7.92	15.75	7.51	16.34	7.39	16.45
9	7.61	16.66	7.15	18.11	7.21	17.32	7.02	17.37	6.94	17.27	7.10	17.18
	7.24	16.95	7.39	16.45	7.52	16.33	7.92	15.75	8.45	15.54	8.51	15.42
	8.05	15.34	8.99	15.71	8.99	16.02	8.44	16.76	8.46	16.97	8.33	16.99
	8.14	17.45	8.20	17.78	7.94	17.73	7.45	17.83	7.15	18.11		
14	6.68	16.93	6.43	18.50	6.47	17.66	6.75	17.37	6.93	17.24	7.01	17.39
	7.20	17.33	7.14	18.09	7.45	17.85	7.94	17.75	8.17	17.74	8.15	17.46
	8.34	16.98	8.48	16.97	8.44	16.80	9.01	16.02	9.26	15.92	9.62	16.12
	9.59	16.54	9.40	16.96	8.65	17.40	8.54	18.03	7.89	18.11	7.54	18.14
	7.27	18.53	6.43	18.50								
16	7.49	18.34	7.26	18.54	7.53	18.13	7.89	18.12	7.61	18.51	7.26	18.54
7	9.00	17.85	7.60	18.56	7.90	18.12	8.54	18.03	8.66	17.40	9.42	16.95
	9.57	17.54	9.65	17.70	9.82	17.58	9.98	17.77	10.18	17.75	9.70	18.54
	8.51	18.24	8.10	18.28	7.60	18.56						
6	9.82	16.25	9.58	17.56	9.40	16.95	9.56	16.52	9.61	16.13	9.22	15.93
	8.99	16.01	8.98	15.68	8.83	15.34	9.02	15.38	9.17	15.61	9.59	15.87
	10.30	16.07	10.34	16.40	10.09	16.47	10.01	16.70	9.73	16.76	9.58	17.56
13	10.05	15.72	10.31	16.06	9.59	15.91	9.14	15.59	9.00	15.37	9.42	15.39
	9.63	15.53	9.75	15.64	9.93	15.71	10.82	14.85	10.31	16.06		
11	10.64	15.79	10.31	17.10	10.27	16.89	10.03	16.77	10.07	16.45	10.36	16.42
	10.31	16.05	10.62	15.65	10.83	14.85	10.85	14.77	11.32	14.83	11.09	15.12
	11.05	15.39	10.90	15.60	10.93	15.83	10.57	16.12	10.54	16.46	10.29	16.68
	10.59	16.93	10.31	17.10								
17	9.71	17.17	9.64	17.69	9.57	17.55	9.71	16.73	9.99	16.69	9.82	17.60
	9.64	17.69										
5	10.00	17.18	9.98	17.76	9.81	17.60	9.98	16.71	10.26	16.85	10.31	17.07
	10.19	17.75	9.98	17.76								
15	11.02	15.64	9.71	18.56	10.19	17.73	10.31	17.08	10.40	16.93	10.31	16.69
	10.57	16.48	10.60	16.13	10.95	15.83	10.90	15.60	11.05	15.40	11.09	15.09
	11.32	14.81	11.46	14.78	11.62	14.49	11.94	14.55	11.39	15.01	11.21	15.62
	10.82	16.28	10.91	16.55	10.84	16.60	10.67	16.56	10.55	16.96	10.57	17.18
	10.35	17.58	10.34	18.36	9.71	18.56						
9	11.32	15.24	10.34	18.40	10.32	17.55	10.58	17.16	10.56	16.93	10.66	16.58
	10.84	16.61	10.92	16.54	10.84	16.24	11.23	15.81	11.39	15.00	11.97	14.53
	12.13	14.81	12.49	14.94	12.53	15.09	12.06	15.79	11.85	15.63	11.60	16.26
	11.63	16.62	11.09	17.58	10.34	18.40						
12	12.51	15.38	12.81	15.37	12.50	15.06	12.03	15.77	11.85	15.82	11.60	16.32
	11.61	16.61	12.26	15.77	12.70	15.54	12.81	15.37				
15	13.02	14.79	12.83	14.68	12.89	14.51	13.03	14.57	13.29	14.92	13.61	15.06
	13.55	15.20	13.14	14.94	13.00	14.90	12.83	14.88				
17	14.32	15.44	13.42	15.96	13.89	15.47	13.85	15.31	13.99	15.06	14.29	15.04
	14.59	14.65	15.11	15.32	14.68	15.82	14.73	16.07	13.76	16.14	13.42	15.96

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   13.40 15.96 13.07 13.58
 2 15.19 15.92 15.13 16.07 15.06 15.78 15.34 15.91 15.32 15.91 15.13 16.07

 8 15.58 14.44 14.71 16.06 14.68 15.02 15.10 15.34 14.62 14.60 14.48 14.55
   14.24 14.73 14.11 14.54 14.20 14.40 14.89 14.30 15.16 14.29 15.88 13.79
   16.31 14.14 17.06 13.00 17.06 13.25 16.69 13.98 16.61 14.65 15.34 15.93
   15.09 15.77 15.16 16.06 14.71 16.06
16 13.15 14.28 13.11 15.55 12.84 15.37 12.52 15.11 12.49 14.97 12.16 14.28
   12.54 14.17 13.01 14.11 12.98 13.98 13.22 13.93 13.42 13.79 13.71 13.85
   14.01 14.18 14.27 14.17 14.51 13.99 14.91 14.31 14.18 14.41 14.14 14.57
   14.22 14.74 13.60 15.04 13.27 14.89 13.03 14.58 12.89 14.48 12.86 14.87
   13.15 14.95 13.56 15.20 13.40 15.43 13.40 15.43 13.11 15.55
 2 13.02 13.77 12.75 13.76 12.90 13.66 13.25 13.60 13.38 13.76 13.23 13.91
   12.98 14.00 12.75 13.76
17 13.36 13.75 14.18 13.83 13.38 13.76 13.70 13.89 14.01 14.17 14.30 14.19
   14.53 14.03 14.83 13.59 14.74 13.27 14.38 13.36 14.26 13.49 14.16 13.46
   13.01 13.67 14.18 13.83
 4 1
   14.19 12.78 14.29 12.93 14.42 12.97 14.45 13.08 14.36 13.34 14.27 13.[illegible]

13 13.36 12.46 14.26 10.67 13.78 11.30 13.44 11.54 13.08 12.15 13.05 12.47
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   14.29 12.93 14.41 12.94 14.46 13.09 14.37 13.35 14.75 13.27 14.74 12.85
   14.44 12.55 14.21 11.27 14.32 10.94 14.26 10.67
15 14.66  8.87 13.07 12.17 13.02 11.79 12.63 11.83 12.88 11.63 13.35 11.49
   13.33 11.29 13.45 11.29 14.07 10.83 14.11 10.62 14.07 10.26 14.30 10.20
   14.41  9.80 14.61  9.18 14.53  8.90 14.69  8.66 14.71  7.62 14.94  7.56
   15.32  7.65 15.22  7.81 14.90  7.90 15.11  8.32 14.74  9.66 14.24 10.66
   13.78 11.32 13.45 11.54 13.07 12.17
 5 15.41 10.04 15.69 10.51 15.50 10.43 15.43 10.21 14.95  9.69 14.98  9.23
   15.21  9.65 15.56  9.86 15.83  9.82 15.91  9.99 15.94 10.27 15.77 10.48
   15.69 10.51
16 15.83  9.83 16.63  9.68 16.65  9.89 16.91  9.82 17.18  9.97 17.20 10.45
   17.36 10.65 17.15 10.64 17.11 10.47 16.97 10.36 16.77 10.09 16.58 10.17
   16.33 10.07 15.94 10.26 15.90 10.03 15.86  9.64 16.63  9.68
 2 16.56 11.08 16.45 11.35 16.27 11.01 16.59 10.97 16.71 10.89 17.01 11.00
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16 15.90 11.89 17.06 11.58 16.77 11.53 16.74 11.72 16.58 11.72 16.58 11.90
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   17.46 10.98 17.40 11.28 17.06 11.58
15 15.28 13.36 14.53 14.04 14.83 13.61 14.72 13.27 14.73 12.86 14.76 12.69
   14.95 12.78 14.99 13.03 15.19 12.93 15.10 12.68 15.31 12.57 15.54 12.78
   15.70 12.42 15.88 12.37 16.14 12.48 16.17 12.13 16.59 11.89 16.64 12.11
   16.10 12.80 15.95 13.17 15.07 13.83 15.16 14.28 14.94 14.33 14.53 14.04

11 16.33 13.03 16.34 14.17 15.85 13.81 15.91 13.13 16.11 12.80 16.62 12.09
   16.58 11.89 16.59 11.75 16.74 11.72 16.78 11.51 17.02 11.59 16.77 12.16
```

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   17.08 13.00 16.34 14.17
 7 14.79 10.90 15.01  7.98 15.20  7.82 14.91  7.91 15.10  8.31 14.77  9.67
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   14.75 12.42 14.81 12.23 15.38 12.09 15.82 11.67 16.43 11.32 16.25 11.03
   16.50 10.97 16.73 10.90 17.00 10.99 17.14 11.13 17.46 10.95 17.37 10.66
   17.13 10.64 17.13 10.49 16.96 10.37 16.77 10.09 16.59 10.17 16.34 10.09
   15.92 10.29 15.69 10.52 15.55 10.48 15.41 10.18 14.93  9.65 15.00  9.23
   15.25  9.67 15.54  9.85 15.88  9.84 16.62  9.68 16.67  9.90 16.90  9.79
   17.17  9.98 17.16  9.54 16.02  8.10 15.01  7.98
 5 12.59 15.28 15.28  4.90 15.16  5.11 14.92  5.07 14.43  5.49 13.72  5.61
   13.16  5.58 12.83  5.49 12.72  5.71 12.89  5.95 12.82  6.43 13.32  7.03
   12.98  7.60 12.82  7.67 12.64  8.57 12.36  8.73 12.14  9.15 11.54  9.69
   11.52  9.45 11.57  9.08 11.38  9.32 11.41  9.82 11.33 10.00 11.17 10.11
   11.32 10.23 11.59 10.83 11.96 11.09 11.93 11.53 11,80 11.77 11.56 11.33
   11.33 11.25 11.08 10.78 10.86 11.19 10.50 11.52 10.73 11.61 11.21 11.74
   11.52 11.74 11.87 12.12 11.51 13.13 11.41 13.63 10.64 13.86 10.62 12.96
   10.54 12.69 10.59 12.40 10.31 12.48 10.08 12.40 10.21 12.71 10.20 12.88
    9.93 12.84 10.12 13.11 10.25 13.76  9.98 14.37  9.35 14.68  9.05 15.23
    9.00 15.38  9.44 15.60  9.61 15.52  9.75 15.63  9.90 15.71 10.83 14.89
   10.88 14.77 11.30 14.80 11.46 14.81 11.63 14.49 11.93 14.52 12.13 14.80
   12.51 14.94 12.13 14.23 12.53 14.14 13.01 14.10 12.97 13.98 12.75 13.74
   12.89 13.65 12.93 13.37 12.81 12.94 13.06 12.50 13.08 12.10 13.01 11.63
   12.62 11.85 12.89 11.61 13.35 11.49 13.34 11.31 13.45 11.29 14.06 10.85
   14.14 10.65 14.10 10.26 14.28 10.17 14.42  9.80 14.59  9.16 14.54  8.86
   14.68  8.66 14.69  7.63 14.95  7.58 15.33  7.62 16.02  7.12 16.79  6.94
   17.04  6.70 16.02  6.09 15.65  5.53 15.65  5.53 15.28  4.90
```
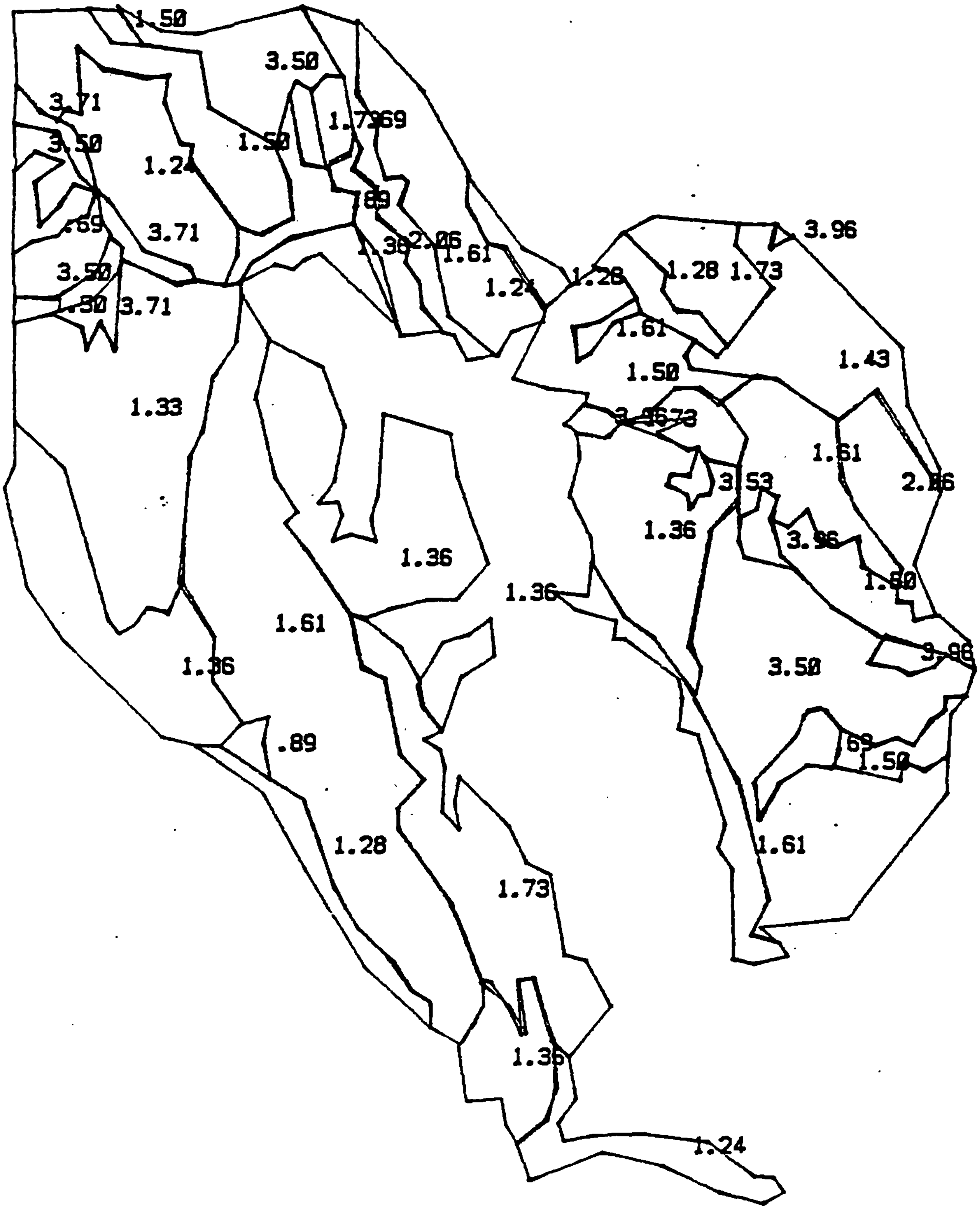

SAMPLE PLOT (#1)

STUDY AREA 1 GALLATIN LANDSLIDE PROJECT



SAMPLE PRINTED REPORT (#1)

STUDY AREA 1 GALLATIN LANDSLIDE PROJECT

6.28 19.59 4.36 19.52

POLYGON			F.S.	P.F.	CODE
1	8.08	10.90	1.36	0.00	86-2D
2	9.02	10.02	.89	92.15	71-1D
3	9.82	8.85	1.28	.47	86-2C
4	9.14	11.39	1.61	0.00	87-2B
5	7.47	13.88	1.33	.42	85-2B
6	11.89	6.40	1.36	0.00	86-2D
7	13.96	5.40	1.24	.22	22-3A
8	11.71	8.35	1.73	0.00	87-2D
9	11.78	11.75	1.36	0.00	86-2D
10	10.56	12.14	1.36	0.00	86-2D
11	7.36	15.03	3.71	0.00	64-2C
12	6.60	15.06	1.50	0.00	87-2A
13	6.65	15.43	3.50	0.00	82-2B
14	6.56	15.98	.69	100.00	71-1A
15	6.54	16.91	3.50	0.00	82-2B
16	6.55	17.39	3.71	0.00	64-2C
17	7.68	15.88	3.71	0.00	64-2C
18	7.61	16.66	1.24	.25	85-2A
19	8.68	16.93	1.50	0.00	87-2A
20	7.49	18.34	1.50	0.00	87-2C
21	9.00	17.85	3.50	0.00	82-2B
22	9.82	16.25	.89	92.15	71-1D
23	10.05	15.72	1.36	0.00	86-2D
24	10.64	15.79	2.06	0.00	86-2A
25	9.71	17.17	1.73	0.00	87-2D
26	10.00	17.18	.69	100.00	71-1A
27	11.02	15.64	1.61	0.00	87-2B
28	11.52	15.24	1.24	.25	85-2A
29	12.51	15.38	1.28	.47	86-2C
30	13.02	14.79	1.61	0.00	87-2B
31	14.32	15.44	1.73	0.00	87-2D
32	13.60	15.45	1.28	.47	86-2C
33	15.19	15.92	3.96	0.00	64-2A
34	15.58	14.44	1.43	0.00	84-1A
35	13.15	14.28	1.50	0.00	87-2C
36	13.02	13.77	3.96	0.00	64-2A
37	13.36	13.75	1.73	0.00	87-2D
38	14.23	13.02	3.53	0.00	66-1A
39	13.36	12.46	1.36	0.00	86-2D
40	14.66	8.87	1.61	0.00	87-2B
41	15.41	10.04	.69	100.00	71-1A
42	15.83	9.83	1.50	0.00	87-2C
43	16.56	11.08	3.96	0.00	64-2A
44	15.00	12.35	3.96	0.00	64-2A
45	15.90	11.89	1.50	0.00	87-2C
46	15.28	13.36	1.61	0.00	87-2B
47	16.33	13.03	2.06	0.00	86-2A
48	14.79	10.90	3.50	0.00	82-2B

SAMPLE POLYGON FILE (#2)

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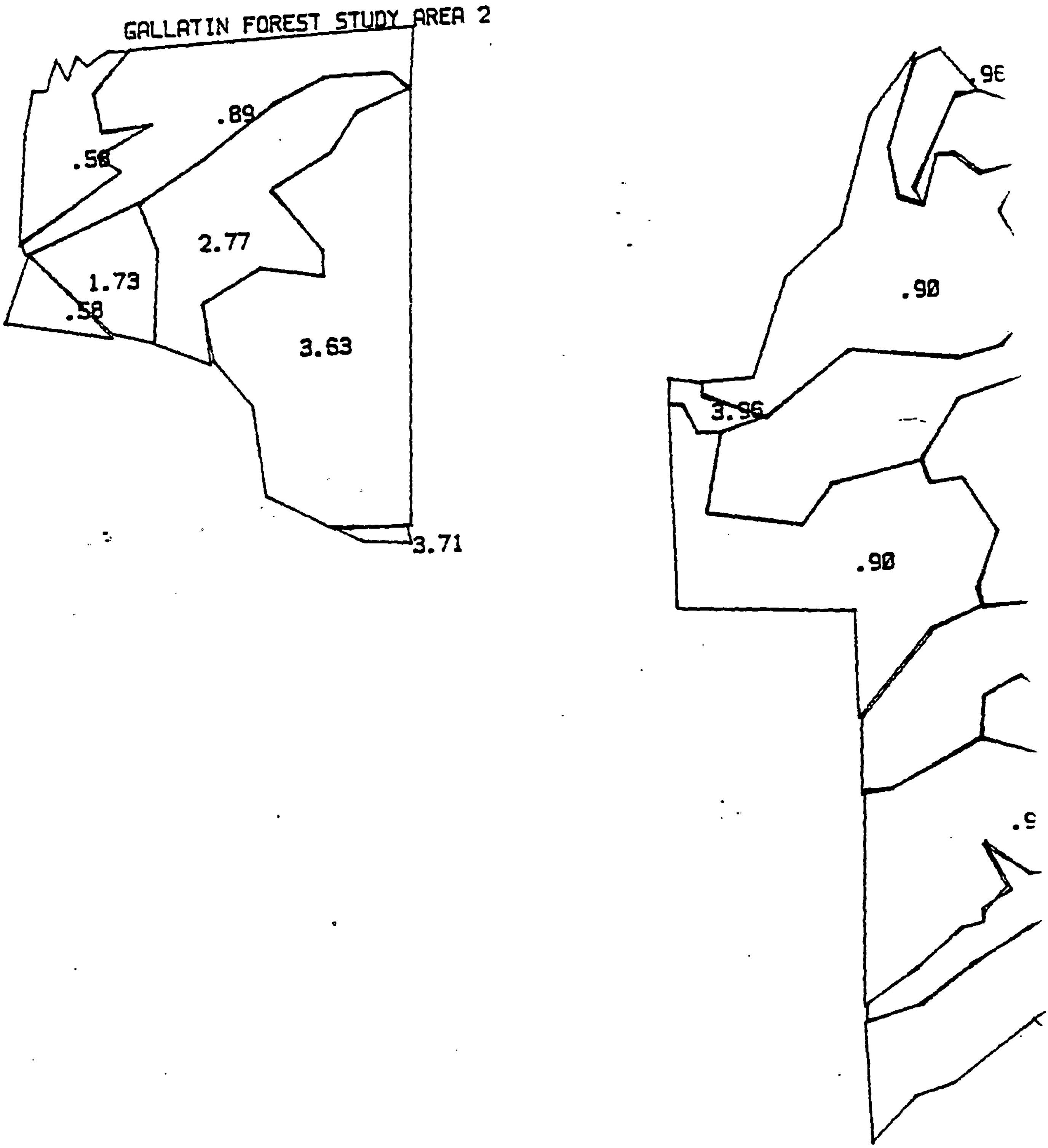
GALAREA2.VTX

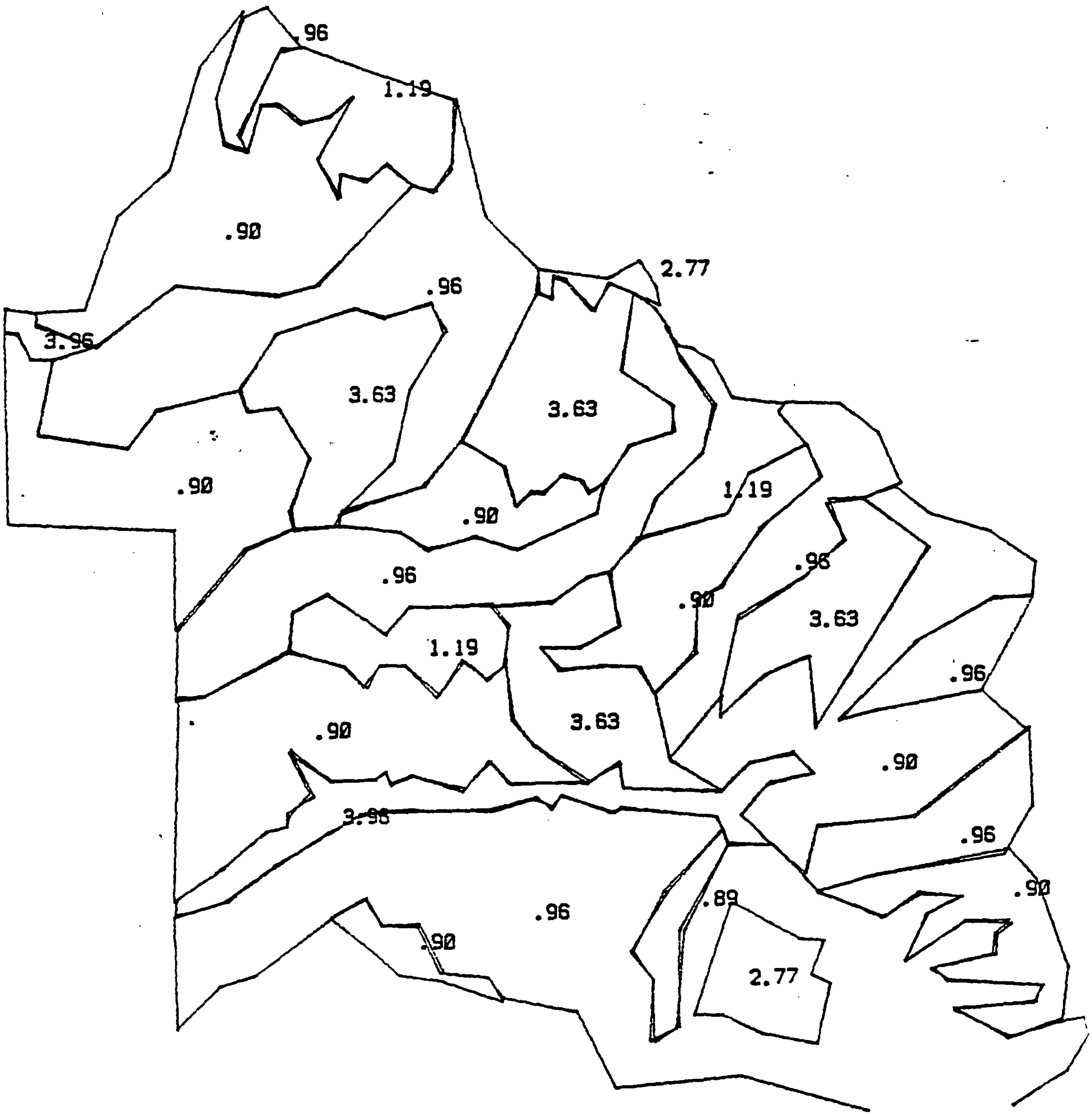
GALLATIN FOREST STUDY AREA 2
     15.51         1.93      22.97        3.05
    200.00         0.00     200.00        0.00
 27  4.27 13.45  4.30 14.24  4.20 13.00  4.10 12.65  5.17 13.38  4.94 13.54
     5.48 13.84  4.99 13.78  4.93 14.19  5.30 14.61  5.10 14.63  4.86 14.40
     4.76 14.59  4.66 14.34  4.55 14.56  4.44 14.24  4.30 14.24
 20  5.76 13.84  5.31 14.03  4.91 14.19  4.99 13.80  5.31 13.85  4.93 13.54
     5.17 13.37  4.12 12.69  4.16 12.55  5.34 13.04  6.05 13.49  6.76 14.01
     7.29 14.26  7.98 14.27  8.19 14.10  8.24 14.74  5.31 14.63
 27  4.13 11.88  3.92 11.86  4.19 12.55  5.02 11.65  3.93 11.86
 26  4.52 12.17  4.20 12.55  5.02 11.69  5.45 11.58  5.51 12.54  5.34 13.05
     4.20 12.55
 24  5.67 12.52  5.35 13.03  5.52 12.55  5.44 11.57  6.01 11.33  5.96 11.97
     6.56 12.30  7.21 12.20  7.21 12.46  6.71 13.13  7.34 13.48  7.61 13.89
     8.16 14.10  7.98 14.28  7.30 14.26  6.74 13.98  6.04 13.47  5.35 13.03
 21  6.67 11.39  6.05 11.36  6.43 10.87  6.53  9.95  7.22  9.57  8.02  9.59
     8.19 14.11  7.61 13.87  7.32 13.48  6.70 13.10  7.21 12.47  7.21 12.20
     6.56 12.31  5.95 11.95  6.05 11.36
  3  7.76  9.30  8.01  9.40  7.52  9.44  7.18  9.60  7.98  9.57  8.01  9.40
 18 10.90 10.55 10.75 10.98 10.73 10.72 10.88 10.70 11.01 10.42 11.23 10.41
    11.72 10.55 11.07 10.79 11.08 10.93 10.76 10.98 10.75 10.98
 22 12.75 11.73 13.39 14.23 12.90 13.61 12.56 12.49 11.98 11.98 11.61 10.96
    11.08 10.94 11.09 10.81 11.73 10.[illegible] 12.[illegible] 11.21 13.71 11.07 14.14 11.18
    15.26 12.28 14.95 12.51 14.73 12.32 14.44 12.42 14.43 12.16 14.19 12.58
    14.59 13.27 14.32 13.05 14.01 12.97 13.74 13.18 13.57 13.18 13.43 12.68
    13.17 12.79 13.09 13.27 13.39 14.23
 23 13.52 13.92 13.40 14.17 13.08 13.26 13.16 12.75 13.41 12.66 13.34 12.85
    13.77 13.77 14.02 13.83 13.65 14.27 13.40 14.17
 25 14.67 13.28 14.59 13.26 14.18 12.58 14.40 12.14 14.43 12.41 14.76 12.35
    14.97 12.52 15.25 12.28 15.48 12.19 15.70 12.52 15.72 13.22 14.05 13.82
    13.80 13.81 13.31 12.86 13.42 12.67 13.57 13.19 13.76 13.20 14.03 12.99
    14.32 13.04 14.59 13.26
 22 12.18  8.92 12.56  8.50 10.74  8.60 10.73 10.73 10.88 10.72 11.02 10.42
    11.25 10.42 11.07  9.57 12.06  9.41 12.37  9.84 13.30 10.03 13.37  9.80
    13.71  9.84 14.05  9.27 13.85  8.68 13.89  8.50 13.34  8.29 12.55  7.40
    12.56  8.50
 23 14.98 11.09 15.45 10.97 15.58 10.64 15.19 10.00 15.01  9.21 14.36  8.63
    15.35  8.95 15.74  9.43 16.61 11.04 16.65 11.33 16.05 11.92 15.75 13.22
    15.68 12.45 15.51 12.21 15.25 12.27 14.18 11.19 13.75 11.09 12.61 11.21
    11.74 10.57 11.25 10.40 11.09  9.58 12.06  9.42 12.39  9.83 13.29 10.04
    13.71 10.66 14.58 10.93 14.91 10.83 14.91 10.82 14.91 10.82 15.45 10.97
 21 14.23  9.90 14.22  8.51 14.38  8.64 15.01  9.23 15.19 10.01 15.61 10.67
    15.43 10.98 14.93 10.81 14.58 10.92 13.70 10.65 13.31 10.03 13.40  9.80
    13.72  9.84 14.06  9.27 13.82  8.68 13.87  8.40 14.32  8.51
 21 16.47  9.71 15.77  9.44 16.22  9.14 16.35  8.70 16.53  8.85 16.68  8.84
    16.86  9.04 17.11  8.98 17.18  8.86 17.34  8.96 17.64  9.37 18.09  9.50
    18.11  9.80 17.54 10.20 17.69 11.05 17.42 11.17 17.26 10.86 16.94 11.22
    16.81 11.26 16.80 11.01 16.63 11.06 16.61 11.04 15.77  9.44
 24 17.73 11.25 17.97 10.92 17.58 11.05 17.45 11.17 17.23 10.86 16.94 11.19
    16.81 11.24 16.78 11.00 16.65 11.08 16.65 11.33 17.40 11.22 17.76 11.41
    17.94 11.12 17.97 10.92
 22 15.34  8.55 14.37  8.52 14.40  8.68 15.31  8.94 15.74  9.44 16.24  9.15
    16.36  8.71 16.53  8.88 16.67  8.86 16.90  9.06 17.08  8.99 17.17  8.84
    17.33  8.95 17.25  8.62 16.36  8.23 15.90  8.39 15.37  8.24 15.07  8.44
```

	14.37	3.52									
23	14.44	7.90	12.58	7.40	13.37	8.28	13.89	8.50	14.33	8.52	15.08	8.43
	15.37	8.25	15.91	8.37	16.38	8.24	17.25	8.63	17.35	8.95	17.61	9.36
	18.12	9.52	18.10	9.80	17.55	10.18	17.69	11.06	17.92	10.80	18.07	10.67
	[illegible]	[illegible]	[illegible]	[illegible]	18.42	9.27	17.90	8.78	17.72	8.32	17.39	7.97
	[illegible]	7.92	16.76	7.56	16.08	7.62	15.16	7.61	14.38	7.31	14.02	7.77
	13.85	7.58	13.79	7.15	12.86	6.65	12.55	6.61	12.50	7.40		
25	18.37	8.79	17.71	8.38	18.69	8.60	18.93	9.04	19.55	9.35	19.26	9.70
	19.32	9.81	18.75	9.88	18.54	10.30	18.33	10.43	18.17	10.47	18.03	10.58
	18.21	10.32	18.57	9.80	18.42	9.28	17.91	8.77	17.71	8.33		
25	15.10	7.09	15.10	6.96	15.45	6.60	15.76	7.01	16.01	6.80	16.19	6.95
	16.26	7.40	16.07	7.64	15.15	7.60	14.90	7.30	14.22	7.76	13.84	7.56
	13.92	7.14	14.41	6.95	14.62	6.72	14.82	6.96	15.10	6.96		
21	16.67	6.24	17.11	5.62	16.53	6.05	16.27	6.34	16.22	6.98	16.25	7.38
	16.06	7.61	16.74	7.63	17.14	7.92	17.40	7.97	17.48	7.36	17.05	7.13
	16.52	7.14	16.82	6.88	17.28	6.93	17.71	6.91	17.87	6.60	18.02	5.87
	18.58	5.53	17.50	5.57	17.46	5.06	17.11	5.62				
22	17.73	7.57	17.70	8.34	18.69	8.60	18.93	9.04	19.57	9.25	19.71	8.93
	19.07	8.44	18.59	7.78	18.34	7.66	18.33	7.06	17.87	6.60	17.67	6.92
	17.28	6.92	16.84	6.90	16.62	7.14	17.07	7.14	17.50	7.37	17.37	7.94
	17.70	8.34										
23	19.00	7.90	19.04	8.43	19.73	8.99	19.56	9.34	19.26	9.72	19.33	9.82
	19.93	9.00	20.36	9.47	20.60	8.91	20.19	8.74	19.77	8.69	19.98	8.28
	19.49	7.87	18.79	7.46	18.59	6.57	18.01	5.89	17.87	6.62	18.31	7.08
	18.35	7.66	18.62	7.78	19.04	8.43						
21	19.30	7.34	18.58	6.35	18.50	6.57	18.78	7.41	19.50	7.87	19.96	8.30
	19.30	8.74	20.18	8.75	20.89	8.20	20.02	6.84	19.61	6.21	19.55	7.01
	19.06	6.80	18.58	6.35								
23	20.69	6.71	20.28	6.40	21.45	6.60	22.03	7.65	21.58	7.61	20.78	7.17
	19.87	6.30	20.28	6.40								
22	13.67	6.18	12.58	6.65	12.87	6.66	13.80	7.13	14.41	6.96	14.66	6.70
	14.81	6.95	15.11	6.96	15.48	6.64	15.73	7.02	16.00	6.79	16.22	6.96
	16.31	6.32	16.54	6.05	17.14	5.64	16.26	5.63	16.03	5.89	15.75	5.59
	15.18	5.73	14.92	5.62	14.87	5.78	14.75	5.68	14.25	5.69	13.80	6.05
	14.05	5.52	13.75	5.34	13.75	5.19	13.52	5.14	13.06	4.74	12.50	4.37
	12.58	6.65										
22	19.93	5.74	19.59	5.70	19.09	5.61	18.78	5.26	19.12	4.90	19.49	4.56
	19.62	5.11	20.69	5.18	21.95	6.13	21.45	6.59	20.29	6.40	19.88	6.29
	20.73	7.15	21.60	7.63	22.01	7.63	22.06	8.02	21.58	8.36	20.91	8.57
	20.54	8.87	20.18	8.74	20.90	8.19	20.01	6.82	19.63	6.23	19.56	7.00
	19.09	6.81	18.58	6.34	18.60	6.58	18.02	5.80	18.57	5.51	18.91	5.84
	19.37	5.95	19.27	5.93	19.59	5.70						
19	14.10	5.21	13.79	6.02	14.01	5.55	13.78	5.32	13.76	5.20	13.54	5.14
	13.06	4.75	12.53	4.39	12.51	4.21	13.09	4.36	13.61	4.74	14.19	5.10
	14.55	5.29	15.07	5.34	16.04	5.36	16.54	5.48	16.71	5.35	16.93	5.49
	17.40	5.30	17.48	5.36	18.52	5.24	18.59	5.08	18.65	4.93	19.11	4.91
	18.79	5.26	19.07	5.58	19.58	5.71	19.38	5.93	18.89	5.34	18.56	5.51
	17.50	5.57	17.48	5.84	17.10	5.63	16.23	5.64	16.01	5.89	15.72	5.56
	15.16	5.74	14.93	5.64	14.85	5.77	14.74	5.68	14.24	5.68	13.79	6.02
23	16.09	4.12	16.13	3.24	15.96	3.48	15.48	3.53	15.22	4.07	14.80	4.04
	14.62	4.35	14.22	4.13	13.39	3.53	12.98	3.41	12.51	2.95	12.50	4.19
	13.06	4.36	13.61	4.76	14.22	5.10	14.56	5.31	15.07	5.36	16.04	5.34
	16.52	5.46	16.72	5.38	16.83	5.50	17.36	5.30	17.49	5.35	18.52	5.24
	18.59	5.09	17.97	4.39	17.56	3.72	17.40	3.41	17.76	2.74	18.08	2.89

	18.10	3.95	18.63	4.91	19.13	4.91	19.47	4.54	19.61	4.36	20.35	4.06
	20.73	4.33	21.19	4.27	20.83	4.08	20.57	3.56	21.24	4.00	21.72	3.99
	21.56	3.84	21.53	3.61	20.87	3.48	21.02	3.33	22.06	3.25	22.00	3.08
	21.10	3.01	21.71	2.69	22.27	2.04	22.51	2.89	22.56	2.69	22.32	2.30
	21.53	1.80	20.05	1.72	18.75	2.34	17.37	2.23	16.96	3.08	16.13	3.24
33	20.78	4.39	20.67	5.20	19.61	5.09	19.46	4.55	19.61	4.37	20.26	4.53
	21.68	4.74	21.99	5.29	21.97	6.17	20.67	5.20				
72	14.81	3.81	14.79	4.04	14.59	4.35	14.71	4.15	14.97	3.49	15.44	3.44
	16.13	3.20	15.98	3.47	15.43	3.53	15.20	4.04	14.79	4.04		
20	17.94	4.24	17.94	4.41	17.59	3.72	17.80	3.40	17.80	2.72	18.05	2.87
	18.15	3.95	18.64	4.91	18.58	5.09	17.94	4.41				
24	18.59	3.34	18.25	3.02	18.67	4.26	19.41	3.83	19.68	3.81	19.53	3.43
	19.74	3.33	19.58	2.58	18.99	2.80	18.56	3.01	18.25	3.02		
22	21.36	4.27	21.21	4.27	20.81	4.08	20.57	3.56	21.24	3.99	21.74	3.95
	21.58	3.82	21.57	3.61	20.85	3.47	21.05	3.34	22.08	3.26	21.97	3.06
	21.09	3.03	21.68	2.68	22.28	2.88	22.35	3.45	22.02	4.45	21.73	4.80
	20.23	4.53	19.61	4.36	20.32	4.05	20.76	4.31	21.21	4.27		

SAMPLE PLOT (#2).





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2.77

SAMPLE PRINTED REPORT (#2)

GALLATIN FOREST STUDY AREA 2

3.05 22.97 1.93 15.51 (map boundaries)

POLYGON			F.S.	P.F.	CODE
1	4.27	13.45	.58	100.00	91-2B
2	5.76	13.84	.89	92.15	71-1D
3	4.13	11.88	.58	100.00	91-2B
4	4.52	12.17	1.73	0.00	87-2D
5	5.67	12.52	2.77	0.00	86-3B
6	6.67	11.39	3.63	0.00	84-2B
7	7.76	9.30	3.71	0.00	64-2C
8	10.90	10.55	3.96	0.00	64-2A
9	12.75	11.73	.90	92.16	85-3A
10	13.52	13.92	.96	73.57	85-3B
11	14.67	13.28	1.19	1.88	86-3C
12	12.18	8.92	.90	92.16	85-3A
13	14.98	11.09	.96	73.57	85-3B
14	14.23	9.90	3.63	0.00	84-2B
15	16.47	9.71	3.63	0.00	84-2B
16	17.73	11.25	2.77	0.00	86-3B
17	15.34	8.55	.90	92.16	85-3A
18	14.44	7.90	.96	73.57	85-3B
19	18.37	8.79	1.19	1.88	86-3C
20	15.10	7.09	1.19	1.88	86-3C
21	16.67	6.24	3.63	0.00	84-2B
22	17.73	7.57	.90	92.16	85-3A
23	19.00	7.98	.96	73.57	85-3B
24	19.30	7.34	3.63	0.00	84-2B
25	20.69	6.71	.96	73.57	85-3B
26	13.67	6.18	.90	92.16	85-3A
27	19.93	5.74	.90	92.16	85-3A
28	14.10	5.21	3.96	0.00	64-2A
29	16.09	4.12	.96	73.57	85-3B
30	20.78	4.89	.96	73.57	85-3B
31	14.81	3.81	.90	92.16	85-3A
32	17.94	4.24	.89	92.15	71-1D
33	18.59	3.34	2.77	0.00	86-3B
34	21.36	4.27	.90	92.16	85-3A

APPENDIX 2

SAMPLE RUN (SCREEN DUMP OF ACTUAL RUN)

SLIDET

CLEARS TERMINAL SCREEN

E

07/17/84

SLIDES calculates the FACTOR OF SAFETY and PROBABILITY of FAILURE
by landslide using an INFINITE SLOPE ANALYSIS.

REQUIRED INPUT IS A FILE OF POLYGON DATA FOR THE AREA
TO BE ANALYZED, AND A FILE OF PARAMETER DATA FOR THE
CODES TO BE USED.

Please enter the POLYGON data file name : CALAREA2

Please enter the CODE data file name : GALMOD2

Send output to Video screen or Plotter? (P/V) [V] V

Send output to printer? (Y/N) [N] N

CALLATIN FOREST STUDY AREA 2

NORTH =	15.51	200.00
SOUTH =	1.93	0.00
EAST =	22.97	200.00
WEST =	3.05	0.00

************ DELIMIT AREA OF INTEREST **********

0 .. USE BOUNDARIES AS GIVEN
1 .. SPECIFY NEW BOUNDARIES IN MAP UNITS
2 .. SPECIFY NEW BOUNDARIES IN WORLD COORDINATES

Please enter your choice : 0

SCALE = 12.601 12.001 10.778

```
E
POLYGON #:   1  CODE:  27
  CODE =    27  33.00  45.00 190.00   0.00  21.00
POLYGON #:   2  CODE:  20
  CODE =    20  33.00  30.00 190.00  20.00  16.00
POLYGON #:   3  CODE:  27
  CODE =    27  33.00  45.00 190.00   0.00  21.00
POLYGON #:   4  CODE:  26
  CODE =    26   6.00  60.00 190.00  40.00  21.00
POLYGON #:   5  CODE:  24
  CODE =    24  10.00  20.00  90.00  20.00  26.00
POLYGON #:   6  CODE:  21
  CODE =    21   6.00  20.00  90.00   0.00  26.00
POLYGON #:   7  CODE:   3
  CODE =     3  33.00  10.00  48.00   0.00  30.00
POLYGON #:   8  CODE:  18
  CODE =    18  33.00  10.00  48.00   0.00  30.00
POLYGON #:   9  CODE:  22
  CODE =    22  10.00  60.00  90.00   0.00  26.00
POLYGON #:  10  CODE:  23
  CODE =    23  10.00  60.00  90.00  20.00  26.00
POLYGON #:  11  CODE:  25
  CODE =    25  10.00  45.00  90.00   0.00  26.00
POLYGON #:  12  CODE:  22
  CODE =    22  10.00  60.00  90.00   0.00  26.00
POLYGON #:  13  CODE:  23
  CODE =    23  10.00  60.00  90.00  20.00  26.00
POLYGON #:  14  CODE:  21
  CODE =    21   6.00  20.00  90.00   0.00  26.00
POLYGON #:  15  CODE:  21
  CODE =    21   6.00  20.00  90.00   0.00  26.00
POLYGON #:  16  CODE:  24
  CODE =    24  10.00  20.00  90.00  20.00  26.00
POLYGON #:  17  CODE:  22
  CODE =    22  10.00  60.00  90.00   0.00  26.00
POLYGON #:  18  CODE:  23
  CODE =    23  10.00  60.00  90.00  20.00  26.00
POLYGON #:  19  CODE:  25
  CODE =    25  10.00  45.00  90.00   0.00  26.00
POLYGON #:  20  CODE:  25
  CODE =    25  10.00  45.00  90.00   0.00  26.00
POLYGON #:  21  CODE:  21
  CODE =    21   6.00  20.00  90.00   0.00  26.00
POLYGON #:  22  CODE:  22
  CODE =    22  10.00  60.00  90.00   0.00  26.00
POLYGON #:  23  CODE:  23
  CODE =    23  10.00  60.00  90.00  20.00  26.00
POLYGON #:  24  CODE:  21
  CODE =    21   6.00  20.00  90.00   0.00  26.00
POLYGON #:  25  CODE:  23
  CODE =    23  10.00  60.00  90.00  20.00  26.00
POLYGON #:  26  CODE:  22
  CODE =    22  10.00  60.00  90.00   0.00  26.00
POLYGON #:  27  CODE:  22
  CODE =    22  10.00  60.00  90.00   0.00  26.00
POLYGON #:  28  CODE:  18
  CODE =    18  33.00  10.00  48.00   0.00  30.00
POLYGON #:  29  CODE:  23
  CODE =    23  10.00  60.00  90.00  20.00  26.00
POLYGON #:  30  CODE:  23
```

27th code in landtype file

partial echo of data for code –
slope
CS1
CR1
ϕ_1

```
  CODE =    2[illegible]  [illegible]  [illegible]  [illegible]  [illegible]  [illegible]
POLYGON #:  31  CODE:  22
  CODE =    22  10.00  60.00  90.00   0.00  26.00
POLYGON #:  32  CODE:  20
  CODE =    20  [illegible]  30.00 180.00  20.00  16.00
POLYGON #:  33  CODE:  24
  CODE =    24  10.00  20.00  90.00  20.00  26.00
POLYGON #:  34  CODE:  22
  CODE =    22  10.00  60.00  90.00   0.00  26.00

Do you want to Quit or Re-run? (Q/R) [Q] Q

PROCESSING COMPLETE

C.
```

APPENDIX 3

PROGRAM ENVIRONMENT

- HARDWARE
- SOFTWARE

OVERVIEW OF HARDWARE ENVIRONMENT

~~SSISCH was originally developed on and for a Hewlett-Packard HP-41CV handheld computer by Rod Prellwitz. The algorithms have been transported to a micro/mini-computer and implemented in a high-level computer language. The resultant program was much enhanced for input and output capability and flexibility.~~

The hardware that this version of SLIDES ~~SSISCH~~ was developed on is:

- S-100 bus microcomputer — Cromemco System 3
  - 8 bit Z80A CPU
  - 64K bytes read/write (RAM) memory.
- 4 floppy disk drives
  - 2 5-1/4" DSDD — Tandon
  - 2 8" DSDD — Shugart
- printers — NEC 7700Q & Epson MX-100
- alphanumeric terminal — Cromemco 3102
- color RGB monitor — Barco 13" 512x512 res.
- color graphics controller — Digital Graphics CAT-300
- plotter — Houston Instruments DMP-40
- digitizer — Numonics 2300

For interest's sake, this is, essentially, the same system as was the prototype Remote Image Processing System (RIPS) used and specified by the Earth Resources Observation Satellite (EROS) Data Center, U. S. Geological Survey, Sioux Falls, SD. Most of the basic software to drive the color monitor through the CAT board is software developed by EROS Data Center staff as part of the RIPS project. However, that software is hardware-specific, and is not listed or fully described in this manual.

The pen plotter uses the DM/PL language, and its instructions are written to a disk file. The contents of this file are sent to the plotter at a later time. Thus, the plotter is used off-line. This keeps SLIDES cleaner and more transportable, since direct interface with the plotter would be highly machine dependent, whereas simply writing the plotter commands to disk as ASCII strings is not particularly hardware dependent (although it is dependent upon the language to which the plotter responds).

OVERVIEW OF SOFTWARE ENVIRONMENT

OPERATING SYSTEM: CDOS (a CP/M "look-alike")

Probably the only considerations of interest to the SSISCH implementor is that file names are 8 characters long, with an optional 3-character extension. ~~This file naming convention surfaces in SSISCH when opening the level 1 disk file in subprogram READL1.~~

LANGUAGE: Microsoft FORTRAN IV

SSISCH is all written in FORTRAN IV (except for the drivers for the color monitor, which should be available at each installation) in an interactive style, for easy data entry and modifications. Programming for interaction with the terminal is straight-forward and should be easily transported to other systems, since no PEEKing or POKEing or other nasty habits have been employed to check the keyboard or to position the cursor on the screen. Nonetheless, FORTRAN IVs are still not entirely standardized. A few notes on the version we used, and the way that we used it are given following.

Opening Disk Files — CALL OPEN (LUN,NAME,IDR)

LUN is the logical unit number to be associated with the file.
NAME is a BYTE array holding the file name. It must be exactly 11 characters long; the first 8 are the file name (padded with blanks if necessary), and the last three are the file extension (padded if necessary).
IDR is the disk drive (#2 is the "B" drive).

Closing Disk Files — ENDFILE lun effectively does this task.

A note on Logical Unit Numbers — our FORTRAN has a convention concerning these. It is:

unit #		device
2	--	printer
3 - 5	--	terminal (screen and keyboard)
6 - 10	--	disk files

Our convention is a little more restricted: we read and write to unit 3 for the terminal, write to unit 2 for the printer, and write plotter commands to a disk file for off-line plotting using unit 9. Other disk accesses use units 6, 7, 8, and 10 as necessary.

Our FORTRAN allows Hollerith literals in FORMAT and DATA statements. Thus, FORMAT(' Factor of Safety =',F5.2) is valid as well as is FORMAT(20H Factor of Safety =F5.2). Those compilers which don't allow such should be hung up by their toenails.

Most character data ~~is~~ are stored in BYTE arrays, one letter at a time. This should be compatible with any implementation of FORTRAN. However, we have been known to store characters four at a time in INTEGER*4 variables and eight at a time in REAL*8.

While we're on the subject of BYTE variables, it should be pointed out that the programs make substantial use of BYTE, LOGICAL*1, and INTEGER*1 variables. These are three different names for the same data type. Some FORTRANS may allow only one or two of these. No consistency has been strived for in this matter on our part.

If BYTE data types are not available (such as in most (all?) BASICs), don't fear. Their use should not be critical in most cases, but they do save space and are handy in FORTRAN. One case in which a BYTE data type is particularly useful is comparing a stored character with the ASCII code of another character. A character read with an A1 format specifier into a BYTE variable will be stored ~~by~~ as that character's ASCII value (you may check this by writing the character with an I format). If the character is stored in an INTEGER variable of a larger size, it will not be stored as an ASCII value (at least, not on our system), so comparing such a stored character with an ASCII value will not work properly.

Finally, Microsoft FORTRAN allows assignment of hexadecimal values to BYTE variables. We have used this feature to a fair extent, mostly to assign a character to a BYTE variable by specifying its hexadecimal ASCII code, and to compare the value of a BYTE variable with a character. This is a way around FORTRAN IV's limitations of handling characters. For instance, you can't say:

```
BYTVAR = 'N'
IF (BYTVAR.EQ.'Y') ...
```

but these equivalents are valid:

```
BYTVAR = Z'4E'
IF (BYTVAR.EQ.Z'59') ...
```

Of course, all of this is easily handled in BASIC without having to resort to such complications.

APPENDIX 4

LINKAGE TO LEVEL 2.

Level 2 area - can specify level one landtype code file name and pick a landtype code whose data you wish to use. Level 2 program SSISCH will use the pertinent data from the chosen code and allow you to make any modifications. Eventually, those modifications can optionally be recorded externally for possible improvement of the level I data base. This aspect is not yet implemented, however.

Item 4

JMH

TENTATIVE AGENDA

LANDSLIDE MEETING 11-8-84

I. Analysis of soil test data
   A. Reduction and correlation to site features
   B. Application to soil map

II. Landslide Model Application
   A. Run with new parameters developed in I. above
   B. Modify model runs for hands on experience to tune model
      1. New slopes
      2. parameter endpoints
      3. Internal operation familiarization
      4. Prob. of Failure

III. Presentation of Statistical Model of Landslide Occurence
   A. Comparison to Analytical Model
   B. Modification of Analytical or Statistical Model

IV. Future Work Directions

Basic Statistical Theory Behind the Model
H. F. Shovic
11-7-84

The contour intervals selected were randomized. They were spaced to give a relatively uniform coverage of the study area, with no map unit or slope bias. The sample contours averaged 150 ft. in width, measured as slope distance. This varied with topography. The field scientist had no knowledge of map unit boundaries.

Because of the above, the contours enabled unbiased estimation of map unit parameters, subject only to random variation. Parameters are Landslide area/ Map Unit Area and # of landslides/ Map Unit Area.

Probability of failure estimates are possible. Assumptions are as follows:
1. The contour samples are random, independent, and mutually exclusive.
2. The contour samples can be broken into small "point" samples and compared to the number of landslides found on the contour sample. The size is set at 200 feet width (on contour) by the slope distance (150 feet). Two hundred feet was chosen to be larger than the average class 1,2, and 3 landslide width (120 feet), to avoid loss of mutual exclusivity. This gives 30,000 sq ft/ sample. Dividing this into the total contour area gives the number of total sample units. This gives probability of obtaining a landslide in class 1,2, or 3 in the map unit. Classes 1,2, and 3 were used because these are the ones judged to be a hazard to present managment.

No estimates of precision in these estimates have been made to date.

Table 5 SA 1

mn

mMap Unitn	mMap Unit Arean	m% MU Area Samplen	mLS Area/MU Arean	mLS/MU Arean	mLS Hazard Ratingn	mProb. of Failu
22-3A	3.302	4.1	0	0	MODERATE	0
71-1A	80.61	11.7	3.96	.14	HIGH	4.2
87-2B	54.08	11.9	.15	.06	MODERATE	1.8
87-2D	23.95	10.7	11.7	.12	MODERATE	3.5
86-2D	53.28	9.5	.01	.02	MODERATE	.6
64-2A	2.15	5.6	0	0	LOW	0
87-2C	15.47	9.8	5.57	.20	MODERATE	6.0
86-2A	8.47	7.3	2.59	.16	MODERATE	4.8
82-2B	36.38	6.8	4.82	.04	MODERATE	1.2
86-2C	7.68	7.5	0	0	MODERATE	0
71-1D	4.32	10.5	0	0	LOW	0
85-2B	24.29	20.5	0	0	LOW	0
64-2C	1.17	29.7	0	0	LOW	0
87-2A	3.30	15.5	0	0	MODERATE	0
85-2A	10.76	17.8	0	0	LOW	0
84-1A	11.66	9.6	0	0	MODERATE	0
66-1A	.56	0	0	0	LOW	0

Table 6 SA 2

Map Unit	Map Unit Area	% MU Area Sample	LS Area/MU Area	LS/MU Area	LS Hazard Rating	Prob. of Failur
85-3B	136.07	12.1	.41	.05	LOW	1.5
85-3A	112.51	13.2	.06	.03	LOW	.8
64-2A	9.47	4.8	0	0	LOW	0
71-1D	3.22	13.1	0	0	LOW	0
84-2B	45.85	8.9	0	0	LOW	0
86-3B	6.11	7.6	0	0	LOW	0
86-3C	21.52	4.4	0	0	LOW	0

LANDSLIDE RISK/COST PROJECT
STUDY AREA DESCRIPTIONS

5-15-84 H. SHOVIC

AREA 1

General: The Study Area is on the Bozeman District in the northcentral part of the Gallatin National Forest. It is in the northeastern Gallatin Range, and includes about 15 square miles of mountainous land. It is made up of parts of the Bear, Goose, and Trail Creek drainages. There are no measured streams in this Area, but water quality is estimated as moderate to high. All drainages have some roads and logged areas, mostly on the included private land.

Lithology: Most of the area is underlain by thickly bedded sandstone interbedded with thickly bedded shale or mudstone, with some limestone or limy sandstone. These rocks are Cambrian through upper Cretaceous in age, and have been extensively folded and faulted during mountain building periods.

Landforms: The most common landforms are structurally controlled slopes and large ancient landslides. Elevations range from about 6000 to 8000 feet. Slope gradients are gently rolling to steep, with most slopes greater than 15%. There are some flat to gently sloping stream terrace/ flood plain complexes.

Bedrock structure and bedding characteristics largely controls the topography on the structural landforms. Sandstone or limestone beds form ridgetops while shale/mudstone beds form concave swales or small valleys. In places, surface slopes conform closely to the underlying dip of the bedrock. Drainage patterns are parallel to dendritic depending on the degree of bedrock control. There are bedrock outcrops on ridgetops and in areas dominated by limestone and sandstone.

The large ancient landslides are characterized by hummocky, rolling topography. The landscape is irregular with many small ponds, and a disordered or deranged drainage pattern of poorly defined streams.

Vegetation: Most slopes have a dense cover of lodgepole pine and Douglas fir forest, with scattered meadows. Ridgetops and some south facing slopes have a sparse cover of subalpine fir or Douglas fir, respectively. Riparian vegetation occurs in wet draws and along major streams. Common habitat types are ABLA/VASC, ABLA/VAGL, ABLA/LIBO, PSME/SYAL. PSME/PHMA, and FEID/AGCA. Timbered and meadow habitat types are moderately to highly productive.

Soils: Soils are mostly medium to moderately fine textured, with few rock fragments. They are formed in weathered sandstone and shale, or in landslide debris. Soil texture depends on the relative mix of bedrock types, but most have clay accumulation in the subsoil. These soils have high fertility and water holding capacity. Depth to bedrock is 2-20 feet depending on topography, and Unified class is GM to CL, depending on bedrock influence. The classes CH or MH are uncommon.
Where sandstone or limestone dominates the bedrock, soils are medium to moderately coarse textured, with many rock fragments. These are formed in colluvial material weathered from bedrock. These soils have moderate fertility, and low water holding capacity. Depth to bedrock is 2-5 feet, and Unified class is GM to ML, depending on bedrock influence. The classes CL, CH, or MH are uncommon.

AREA 2

General: The Study Area is on the Bozeman District in the northcentral part of the Gallatin National Forest. It is in the mid central Bridger Range, and includes part of the Bangtails. It includes about 14 square miles of mountainous land, and is made up parts of the Olson, White, Stone, Slushman, and Maynard Creek Drainages. Three measured streams (Maynard, Olson, and Stone) all have high water quality. All the drainages have some roads and logged areas, partially on included private lands.

Lithology: Most of the area is underlain by rocks of the Fort Union Formation and the Livingston Group. These rocks are Tertiary in age, and consist of thick beds of dark colored sandstone interbedded with thin beds of shale and claystone or siltstone. They are derived principally from volcanic sediments eroded from the Elkhorn Mountains. They have been folded and faulted during mountain building periods.

Landforms: The most common landforms are structurally controlled slopes. The underlying bedrock structure and lithology largely controls the surface topography. Elevations range from about 6000 to 8000 feet. Gradients are gently rolling to steep, with most slopes greater than 30%. Sandstone beds form ridgetops and shale/mudstone beds form concave swales or small valleys. There are bedrock outcrops on steep side slopes and ridgetops. The drainage system has a dendritic to rectangular pattern with some control by bedrock structure. There are a few large ancient landslides, and some flat to gently sloping stream terrace/ flood plain complexes.

Vegetation: Most slopes have a dense canopy of lodgepole pine or sparse to dense Douglas fir, with some meadows. There are large grassland parks on some broad ridgetops. Common habitat types are ABLA/VAGL, ABLA/VASC, PSME/SYAL, with some ABLA/ARCO, FEID/AGSP, ARTR/FEID, and PSME/AGSP. Timbered habitat types are moderately productive. Grasslands have relatively high productivity.

Soils: Soils are mostly medium to moderately fine textured, with many angular rock fragments. They are formed in colluvial material weathered from sandstone and shale or mudstone bedrock. Soil texture depends on the relative mix of bedrock types. Most soils have clay accumulation in the subsoil. They have moderate fertility and high water holding capacity. Depth to bedrock is 3 to 8 feet, and Unified class is variable, because of the variation in bedrock.

LANDSLIDE PROJECT
STUDY AREA MAP UNITS

Study Area 1

Map Units: There are 17 different Map Units in Study Area 1, and 48 delineations.

Map Unit	Del.	Landslide Hazard
22-3A	1	moderate
64-2A	4	low
64_2C	3	low
66-1A	1	low
71-1A	4	high
71-1D	2	low
82-2B	4	moderate
84-1A	1	moderate
85-2A	2	low
85-2B	1	low
86-2A	2	moderate
86-2C	3	moderate
86-2D	5	moderate
87-2A	2	moderate
87-2B	5	moderate
87-2C	4	moderate
87-2D	4	moderate

Study Area 2

Map Units: There are 10 different Map Units in the Study Area, and 33 delineations.

Map Unit	Del.	Landslide Hazard
64-2A	2	low
64-2C	1	low
71-1D	2	low
84-2B	5	low
85-3A	8	low
85-3B	6	low
86-3B	3	low
86-3C	5	low
87-2D	1	moderate
91-2B	2	moderate

Item 5

United States Department of Agriculture
Forest Service
Forestry Sciences Laboratory
P.O. Box 8089
Missoula, MT 59807

Reply to: 1360 Meetings

Date: February 8, 1985

Subject: Statistics in Slope Stability Analysis Workshop

To: Attendees

The workshop on Statistics in Slope Stability Analysis will meet at the Forestry Sciences Laboratory, Moscow, Idaho, 8:00am, February 28 through March 1. Thanks for agreeing to participant in this workshop.

Historically, slope stability analysis has been largely done with mechanical deterministic methods which predict the factor of safety against failure of a soil or rock mass along some estimated failure surface. In the past few years, probabilistic methodology has been introduced and geotechnical journals are beginning to evidence this. For the Forest Service, there are some real advantages to the probabilistic approach, none the least being:

a) to extend our analysis procedures beyond the established mechanical procedures.
b) as the basis for decision (risk) analysis in the selection of alternate courses of action,
c) for "ground truth" to evaluate how well a deterministic analysis predicts actual slope failure.

Our goal at the workshop will be to develop an action plan to assimilate the probabilistic approach into all three levels of slope stability analysis under development by engineering research and the University of Idaho. Two papers are enclosed which describe the three-level approach and the analysis techniques will be further discussed at the workshop. A list of attendees is attached. The group has been kept small but includes representatives with engineering, geology, soil science and statistical backgrounds. The meeting climate will be that of informal discussion and has been scheduled for two full days if necessary to allow ample involvement of the varied expertise in attendance.

To provide you with some background, I am enclosing (and Terry Howard will be sending you) copies of selected journal articles which apply probability to slope stability analysis. We will be discussing some of these approaches at the meeting. Also enclosed is an outline by Henry Shovic of his mapping unit approach based on frequency of landslides from landslide inventory. We will be discussing this as an approach to provide us the "ground truth" for at least one level of analysis.

To provide some order to the meeting, a proposed tentative agenda is attached. We will have to keep it flexible and adjust the time schedule as the meeting progresses. I'm looking forward to an educational and productive meeting. If you need help with transportation to or from the airport or lodging reservations contact me (FSL Missoula, FTS-585-3485) or Carol Hammond (FSL Moscow, 208/882-3557).

Rodney W. Prellwitz

RODNEY W. PRELLWITZ
Research Engineer

Enclosure

TENTATIVE AGENDA

WORKSHOP ON
STATISTICS IN SLOPE STABILITY

Forestry Sciences Laboratory
1221 So. Main, Moscow, ID

February 28, 1985, 8:00am
thru March 1, 1985, ?

Introduction to the 3 level Slope
Stability Analysis Concept................................ Prellwitz

Current Deterministic Methods in
Slope Stability Analysis .... Howard, Prellwitz, Burroughs

Review of Probabilistic Methods in
Slope Stability Analysis (Journal articles)................. Group
(for background and communication -- geotech. attendees
explain and evaluate deterministic and mechanical and
stat. attendees explain and evaluate the probabilistic)

Slope Stability Parameters, Variable or Set?................. Group

"Ground truth", Mapping and Inventory of Landslide
Frequency, the Gallatin Model .... Shovic

Level I Slope Stability Analysis, Probabilistic Approaches... Group[1]

Level II Slope Stability Analysis, Probabilistic Approaches.. Group[1]

Level III Slope Stability Analysis, Probabilistic Approaches. Group[1]

---

[1]For each level of slope stability analysis, the group will review the deterministic approach and discuss and evaluate applicable probablistic methodology. The results of these group sessions will be used by Engineering research and the University of Idaho to formulate an action plan for assimilation of probabilistic methodology into the three-level slope stability analysis system.

LIST OF ATTENDEES

WORKSHOP ON STATISTICS IN SLOPE STABILITY

Forestry Sciences Laboratory
1221 So. Main, Moscow, ID

February 28, 1985
March 1, 1985

U.S. Forest Service

Gordon Booth, Statistics Group Ldr.
Ogden, UT

Ed Burroughs, Engrg. Research Project Leader
Bozeman, MT

Carol Hammond, Research Geologist
Moscow, ID

Rod Prellwitz, Research Engineer
Missoula, MT

Henry Shovic, Soil Scientist
Gallatin, NF, Bozeman, MT

University of Idaho, Moscow, ID

Jim Hardcastle
Civil Engineering

Terry Howard
Geological Engineering

Stan Miller
Geological Engineering

Clancy Potratz
Mathematics

Item 6

DETERMINATION OF SOIL SHEAR STRENGTHS

A statistical description of a soil's shear strength can be made by testing a number of samples of the soil type in question. The test procedure can be characterized as follows:

A direct shear strength test is performed on a soil sample to determine the shear strength, T, corresponding to various normal stresses, o. Each specimen is tested at four or more normal loads, resulting in a set of values for normal stress (the independent variable) and shear strength (the dependent variable). An iterative procedure based on Newton's method of approximation is used to fit a curve to these direct shear test data.

Although a linear regression is widely used in analysing shear strength, some direct shear data cannot be described adequately by a linear model. We use a modified power curve (Jaeger, 1971 & Miller, 1984), which can be expressed as $y = Ax^B + C$, where x is normal stress; y is predicted shear strength for a given x; and A, B, and C are best estimators of regression parameters. This provides parameters for a least squares regression curve which defines the specimen's expected shear strength at any given normal stress.

It may seem advisable to make a logarithmic transformation of the power curve formula into a linear system and then to apply standard linear regression procedures rather than perform an iterative procedure as is done here. This, however, would minimize the mean squared error-of-estimate for the logarithms of the data values, not of the data values themselves. Although this problem can be compensated for (Pennington, 1970), there remain questions of statistical integrity [are statistical assumptions violated?].

Regression curves from several specimens of the same type are then "combined" to produce a regression curve, and a characterization of the variance, representative of the soil. A modified power curve of the form $y = Ax^B + C$ has been linearized by approximating the power term with the first two terms of a Maclaurin series (Draper & Smith, 1981; Miller, 1984), to yield $y = Ax^{BO} + A(B-BO)x^{BO}\ln x + C$ This equation is used in an iterative procedure, described in Miller (1984), to characterize the soil shear strength. Two 3 x 3 matrices are also generated for use in estimating the expected variance of expected shear strength at any normal stress.

The initial values of A, B, and C are found by applying Newton's method to a number (say 30) of data points, each of which has a normal stress value of x0 between the minimum and maximum normal stresses used in testing and shear strength value equal to the mean of the values predicted at x0 by the regression curves of the individual specimens. The data points are spaced evenly in the normal stress direction.

The parameters for the final regression curve relating normal stress to shear strength and the matrices which characterize the variance in shear strength at any normal stress are then associated with one or more landtypes.

The whole process can be depicted graphically as in Figure xxx.

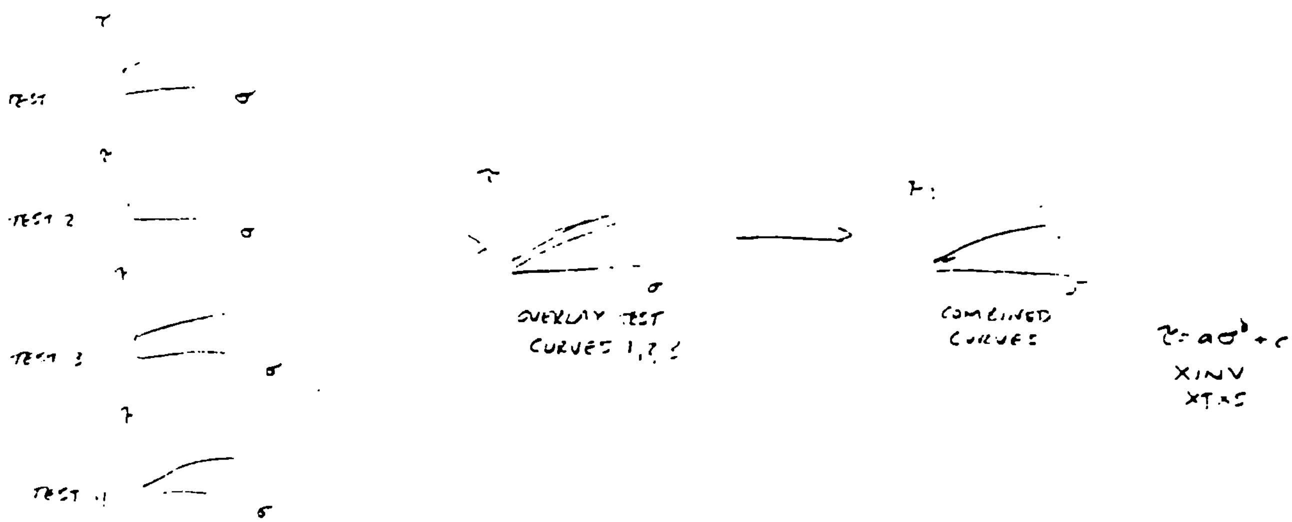

Figure xxx.

==

[Several programs external to SLIDES have been developed to aid in this process. They need to be integrated with each other and with SLIDES some more before the process will work smoothly. At present, the programs are called 1SAMPLE (determine regression curve for test data for individual sample), TAUS3 (combine regression curves from several samples of one soil type into another regression curve representative of the soil), and REGRESS (plot the sample data and the generated regression curve). (As of Sept 19, 1985)]

Item 7

Slides uses a statistical "monte carlo" approach for estimating probability of failure of a land type due to a soil mantle slide. Distributions are specified for the random variables in the infinite slope - factor of safety equation. Uniform, normal, and log-normal distributions are supported: constant values may also be specified. For each random variable, a sequence of values fitting the specified distribution and associated parameters (such as mean and variance) is generated using a pseudo-random number generator. A sequence of factor from of safety values is then calculated using corresponding values for the random variable sequences. An overall probability of failure figure is then the proportion of these factors of safety which have a value of one or less.

The details of the system, of course, turn out to be a little messier than it might first appear. For one thing, soil shear strength is treated as a two-stage random variable. The expected distribution of shear strength values for a soil are determined by the soil's effective normal stress, which in turn is calculated using the primary random variables. Another layer of complexity is added by the fact that the soil layer is broken down into m intervals of equal depth, each with an assumed probability that the groundwater surface will fall within that interval in a given length of time (say 20 years). Each soil interval is treated separately, with the height of the piezometric surface in that interval being treated as a random variable. The final probability of failure for the soil layer as a whole ~~must be a~~ is a combination of the probabilities determined for each soil interval. This approach is used in order to make the probability figures have a real-world meaning (what is the chance that this type of land will fail due to a soil mantle landslide within x years?). It also requires that some type of groundwater/precipitation model be used to determine the probability that the piezometric surface falls within a specific soil interval within a certain time frame. A satisfactory groundwater modelling system seems at least several years off at this point.

maps may be created by specifying a landtype code and outline or a polygon for each landtype ...

[Is probability of failure tied to area or occurance??]

Random variables used in the infinite slope equation are:

- q_0 tree surcharge (as a pressure)
- H soil depth
- C_r root strength
- β ground surface slope
- γ, γ_{sat} soil densities (natural & saturated)
- τ shear strength (as noted above)
- H_w water depth (as noted above)

(Also specify DIMENSIONALITY of variables, and EXAMPLE OF CONSISTENT SYSTEM OF UNITS.)

B & q0 typically uniform or normal; Y,Ysat,H normal; Hw uniform within soil interval boundaries

SLIDESPFMETHD

METHOD USED TO CALCULATE PROBABILITY OF FAILURE -- LEVEL I

DAVID HALL SEPTEMBER 1985

The following steps are done for each landtype:

1. Generate a sequence of *n* pseudo-random numbers, adhering to the specified distribution, for each of the primary random variables: soil depth, soil densities (normal and saturated), ground slope, root strength, and tree surcharge.

2. Divide soil mantle into *m* intervals of uniform depth. For each soil interval:

   a. Generate a sequence of *n* values for groundwater depth distributed uniformly within the interval.

   b. From the sequences of values generated in steps 1 and 2a, calculate a sequence of *n* values for effective normal stress.

   c. From the sequence of effective normal stress, determine *n* values for soil shear strength (for each normal stress, find values for shear strength mean and variance, and randomly pick a value for shear strength, assuming a log-normal distribution for shear strength).

   d. Calculate *n* factors of safety for the soil interval, and determine the proportion of these which indicate a failure (factor not greater than 1.00). This is the probability of failure given that the groundwater is in interval *i*" : P(fail|interval i).

3. Retrieve a table giving a probability for the groundwater level falling within each soil interval in a given time period (say a 20-year period). This is P(interval i)

4. The "incremental probability of failure" S_i for soil interval *i* in the chosen time period is

   $$P[(\text{fail}) \cap (\text{interval } i)] = P(\text{fail}|\text{interval } i) * P(\text{interval } i)$$

5. The overall probability of failure in the chosen time period for the landtype is

   PF = [sum i=1,m] Si

INFINITE SLOPE MODEL

The probability of failure for a specific landtype code is determined in SLIDES by calculating factors of safety for many possible values of input variables using an infinite slope equation. The probability of failure is then the proportion of those calculated factors of safety which were at most one. The basic infinite slope equation used is fairly straight-forward:

$$F.S. = \frac{T + Cr}{[q0 + Y\ (H - Hw) + Ysat\ Hw]\ \sin B \cos B}$$

where

q0	=	surcharge stress
Y	=	unit weight of soil (natural)
Ysat	=	unit weight of soil (saturated)
Yw	=	unit weight of water (used below)
H	=	vertical height of soil layer
Hw	=	vertical height of piezometric surface (from base of soil layer)
B	=	ground surface angle
T	=	normal stress of soil
Cr	=	root cohesion

The soil's normal stress, T, is determined in a two-step process. First, a value for effective normal stress, o', is calculated using the following equation:

$$o' = \cos^2 B\ [\ q0 + Y\ (H - Hw) + (Ysat - Yw)\ Hw\ ]$$

where the variables are as specified above. The effective normal stress values are in turn used to determine a value for shear strength. Direct shear strength tests must be performed on several samples of soil for each landtype code to determine appropriate parameters for a regression curve relating effective normal stress to shear strength. Appropriate parameters will be made available for various unified soil codes (provided we have the time & funding), allowing the user to bypass the expensive and time-consuming tests at the cost of using a relationship between normal stress and shear strength which might not match the soil in question as well as it might. Since this is a broad, level 1 analysis with other imprecisions ~~at least~~, these approximations will probably be satisfactory in most cases. The possibility of adding more precise relations in this area does exist, however, for those who desire it.

Item 8

PSEUDO-RANDOM NUMBER GENERATORS

DAVID HALL APRIL 1985

A number of techniques in applied mathematics and statistics involve what are called Monte Carlo calculations. Such calculations depend on having available sequences of numbers which at least appear to be drawn at random from certain probability distributions. The term "pseudo-random" is often used to describe sequences of numbers which are able to pass tests for randomness, even though the sequences may have been generated by a completely deterministic process. Such pseudo-random number sequences have been described as "a vague notion embodying the idea of a sequence in which each term is unpredictable to the uninitiated and whose digits pass a certain number of tests, traditional with statistitians and depending somewhat on the uses to which the sequence is to be put." [Lehmer[67] as quoted in [5]].

METHODS USED IN UNIFORM PSEUDO-RANDOM NUMBER GENERATORS

There are several common schemes in use on digital computers to generate sequences of pseudo-random numbers. I will briefly describe the empirical, (mixed) congruential, and multiplicative congruential methods.

EMPIRICAL METHOD

One method used occasionally to generate pseudo-random numbers is the empirical method. It is generally computation-intensive, and involves generating in some pseudo-random fashion a multi-digit number, and then using the digits to the right of the decimal point as a number between zero and one. The technique used in [3] is as follows. Take a seed, transform it into a number greater than one (by adding one to the absolute value of the seed), divide this value by the irrational value e, add one, and multiply the sum by the square root of two. This value is then added to the previous random number in the sequence and multiplied by an integer which is incremented upon each invocaton of the subroutine. Multiples of pi and one are then subtracted from the resulting number until a value between 0 and 1 is found. "Even after all these magical steps are performed, the resulting distribution is not entirely uniform, and an empirical correction is performed." There must be a better way.

MIXED CONGRUENTIAL METHOD

A more straight-forward method computationally is the mixed congruential method. Its procedure is as follows. We begin with a positive integer $X0$, an integer A, another integer B, and a modulus T, which is positive and greater in magnitude than the other three. We then define a sequence $\{Xi\}$ of non-negative integers, each less than T, by means of the congruence relation

$$X(i) = AX(i-1) + B \quad (\text{modulo } T) \qquad (1)$$

Finally, we form the sequence $\{Xi/T\}$ to obtain numbers in the interval $[0,1)$.

For many values of the parameters defining such sequences, the resulting numbers might well seem to be quite haphazardly chosen from the interval [0,1). It turns out that the statistical behavior of such sequences is quite good, with few exceptions, as long as the sequences don't repeat too soon. It can be shown that, with T a power of 2 (a desirable choice for a binary computer), we need only have B odd, and A = 1 (modulo 4) in order to have a sequence with full period T. [4]
The choice of T is determined by the capacity and base of the computer. The most convenient choices for A are in the form $A=2^p+1$. This results in the fastest generation of random numbers, and any number can serve as the starting point to generate a sequence of random numbers. [3]

MULTIPLICATIVE CONGRUENTIAL METHOD

A second system of generating sequences of pseudo-random numbers is obtained from (1) by taking B=0. With this type of system, the sequences can not have the full period T, although the period still can be quite large. In addition, the basic theorem is harder to establish, the required conditions are harder to remember, and the lower-significance digits have short periods. On the positive side, if all the conditions are met, there are no statistically unacceptable sequences, whereas there are a few for the mixed congruential method.

ANALYZING PSEUDO-RANDOM NUMBER GENERATORS

A number of statistical tests can be applied to sequences of pseudo-random numbers to determine such things as how well they match a desired distribution and how apparent the correlation is between one number and the next. Such analyses include the Chi-Square tests (which I will not describe further, but which are described in [5]), and the study of moments and of serial correlation.

MOMENTS

Among the more important properties of a theoretical distribution is a set of quantities known as the <u>moments</u> of the distribution. The moments, usually taken with respect to the origin or with respect to the mean, characterize the distribution: if two distributions have the same set of moments, the distributions are identical. In applied statistics, only two of the moments are of any great practical importance: the <u>first moment about the origin</u>, and the <u>second moment about the mean</u>.

The first moment about the origin is the mean of the theoretical distribution. The variance σ^2 of a random variable Y is defined as the second moment about the mean μ, the average value of $(Y-\mu)^2$ [1]
In general, if X1,X2,...,Xn is a random sample from a probability density function f(X), the k^{th} <u>population moment</u>, or k^{th} <u>moment of the distribution</u>, is $E(X^k)$. The k^{th} <u>sample moment</u> (about the origin) is $(1/n) \sum X^k$. [2]
The k^{th} <u>sample moment</u> (about the mean) is $(1/n) \sum (X-\mu)^k$.

The moments for an ideal uniform [0,1] distribution are shown below. Moments calculated for North Star BASIC's RND function on 10 sets of 1000 numbers each, and results from the first 100 numbers generated from function URAN using X0=762939453125 are also given as a comparison.

Moment	Ideal Pop.	North Star RND	URAN
First (mean)	0.500	0.497 +/- .004	0.500
Second (about mean)	0.0833	0.083 +/- .002	0.0821
Third (about mean)	0.0000	-0.0002 +/- .0003	-0.0015

All but the figures for URAN were taken from reference [3].

SERIAL CORRELATION

A low serial correlation, ρ, is often desirable in pseudo-random number sequences. In the congruence method setting, it has been noted that very small or very large values of A are to be avoided, and that values of A near $T^{0.5}$ will yield small values of ρ regardless of the value of B. The equation given for serial correlation of lag 1 (the correlation between sequential pseudo-random numbers) is

$$\rho = \frac{(1-6*(B/T)) * (1-(B/T))}{A} + E$$

where $|E| < A/T$. [4]

It has also been shown that the sequence consisting of every k^{th} member of the original sequence is itself a sequence of the form (1), but with $A = A^k$ and $B = (A^k-1)*B/(A-1)$. Both parameters should be calculated modulo T. [5] Using this fact, serial correlations of lags greater than one can be determined. In addition, analyses of the likely statistical behavior of sequences of every k^{th} member of the original sequence can be done.

A GENERAL-PURPOSE PSEUDO-RANDOM UNIFORM [0,1] NUMBER GENERATOR

URAN is a function subprogram written in FORTRAN which generates numbers which fit a uniform distribution of range [0,1] in a reasonably random fashion. It is based on the mixed congruential method, and is of the family

A: $= 1+t^p$
B: odd
T: $= t^q$
period: t^q
X0: $0<X0<T$

The number sequence generated with X0 = 762,939,453,125; B=29741096258473, p=9; and q=47 has passed statistical tests for randomness. [4] These are the figures used in URAN.

```
C
      FUNCTION URAN(X0)
C
C     UNIFORM [0,1] PSEUDO-RANDOM NUMBER GENERATOR.
C     CALL WITH SEED VALUE FOR FIRST CALL (X0)
C     THEN USE THE X0 GENERATED FROM PREVIOUS CALL.
C     SEED OF X0=762939453125 HAS PASSED STATISTICAL TESTS
C
      REAL*8 T,X0,B
C
C  T=2**47;  A=(2**9)+1
C
      DATA B/29741096258473./
      DATA T/140737488355328./
      DATA A/513./
      X=AMOD((A*X0+B),T)
      URAN=(X0/T)
      RETURN
      END
```

A sample calling program follows.

```
      PROGRAM RANDOM
      REAL*8 R,SUM,X0
C   GET SEED VALUE
      WRITE(*,*) ' STORE UNIFORM [0,1] NUMBERS ON DISK ... HOW MANY? '
      READ(*,*) NV
      WRITE(*,*) ' Please enter random number seed (0 for proven #) '
      READ(*,*) X0
      IF (X0.EQ.0.0) X0=762939453125.
      SUM=0.
      OPEN (3,FILE='B:FORTDAT',FORM='BINARY')
      DO 100 I=1,NV
      R=URAN(X0)
      SUM=SUM+R
  100 WRITE(3) R
      WRITE(*,*) ' MEAN IS ', SUM/FLOAT(NV)
      STOP
      END
```

A PSEUDO-RANDOM, INDEPENDENT NORMAL [0,1] NUMBER GENERATOR

In principal at least, it is easy to obtain any other distribution from the uniform distribution. For one-dimensional distributions, we need only solve the equation X=F(Y) for Y, where X is uniformly distributed, and where F is the required cumulative distribution function.

There are several methods in existance to obtain normal deviates. One method is to take a sum of a fixed number of uniform variates. By the Central Limit Theorem, this sum is approximately normally distributed. This is the system used by the normal random number subroutine in [3]. A Chebyshev polynomial can subsequently be used to improve the approximation. Another method employs different Chebyshev approximations over different intervals to obtain a normal distribution. Function RANINO uses a rational approximation to create a normal distribution.

```
      FUNCTION RANINO(X0)
C
C   GENERATE ONE OF A SERIES OF PSEUDO-RANDOM INDEPENDENT NORMAL [0,1]
C   NUMBERS.
C
C   CALLS FUNCTION URAN
C
      REAL*8 X0
      U1=URAN(X0)
      UN=U1
      IF(U1.GT.0.5) UN=1.-U1
      Y=SQRT(-2.*ALOG(UN))
      ZNUM=2.515517+0.802853*Y+0.010328*Y*Y
      ZDEN=1.+1.432788*Y+0.189269*Y*Y+0.0013083*Y**3.
      RN=Y-(ZNUM/ZDEN)
      IF(U1.LE.0.5) RN=-RN
      RANINO=RN
      RETURN
      END
```

CONVERTING U[0,1] TO U[MIN,MAX] AND N[0,1] TO N[μ,σ^2]

To convert a number U from a uniform distribution of range zero to one to an equivalent number U' from a uniform distribution of range MIN to MAX, or with a given center and spread, use the following equation:

U' = MIN + U * (MAX-MIN)

or U' = CENTER + SPREAD * (U-0.5).

To convert a number N from a normal distribution of mean 0 and variance 1 to an equivalent number N' taken from a normal distribution of mean μ and variance σ^2, use:

$N' = \sigma * N + \mu$

Analysis of URAN Random Number Generator for use in the Level I Analysis

Subroutine URAN is based on the mixed congruential method of generating sequences of pseudo-random numbers of approximately uniform distribution in the zero-to-one range; that is, it uses the formula

$$X(i) = AX(i-1) + B \quad (\text{modulo } T)$$

to derive one number in the sequence from the previous one. The statistical behavior of such sequences is quite good, with few exceptions, if T is a power of two, A (modulo 4) = 1, and B is odd. This will yield a sequence of numbers with period T.

In order to have low "serial correlation" (low apparent correlation between one generated number and the next), very small and very large values of A should be avoided. Values of A near $T^{0.5}$ have been shown to yield low serial correlations regardless of the value of B; [5] correlation of lag one will be approximately $T^{-0.5}$.

The values of A, B, T, and X0 as used in function URAN have reportedly been validated statistically for randomness [4]. Since A is fairly small (nowhere near $T^{0.5}$), and since no mention was made regarding which tests were performed, we aren't sure that a test of serial correlation was included. We assume that every consecutive sequence of the generated numbers, if it is reasonably long, will also behave fairly well in appropriate statistical tests. However, the same can not necessarily be said of sequences consisting of every $\underline{k}^{th}$ member of the original sequence.

The tests done so far on the moments of the number sequences generated by URAN have looked acceptable, as shown in Table 1.

Seed	Sequence size	First moment	Second moment
(ideal)		0.500	0.0833
762939453125	100	0.500	0.0821
762939453125	1000	0.496	0.079
8953145723	100	0.501	0.083
83	100	0.501	0.070
762939453125	1000		
every second, starting with X0:		0.499	0.077
every second, starting with X1:		0.493	0.080
every fifth, starting with X0:		0.478	0.085
every fifth, starting with X1:		0.517	0.080

Table 1. Preliminary analysis of moments of URAN sequences.

TWO METHODS TO CALCULATE SEQUENCES OF FACTOR OF SAFETY FIGURES

METHOD ONE -- WORK ON ONE TRIAL AT A TIME

One method to calculate a series of factor of safety figures based on random samplings of random variables is to choose one value from the specified distribution of each random variable (soil depth, slope, etc.), calculate the corresponding factor of safety figure, and repeat the process, say, 500 times, as shown in Table 2.

Random Variable	trial 1	trial 2	trial 3	trial 4	...
tree surcharge	X0	X6	X12	X18	...
slope	X1	X7	X13	...	
soil cohesion	X2	X8	X14	...	
soil depth	X3	X9	X15	...	
soil density sat.	X4	X10	X16	...	
soil density dry	X5	X11	X17	...	

Table 2. Possible order in which variables are assigned values from pseudo-random number sequence (Xi)

If this scheme were implemented, the pseudo-random numbers used for each particular random variable would be based on the sequence of every k^{th} number generated by URAN, k being the number of random variables (plus one). Such a sequence is itself a sequence of the mixed congruential form

$$X'(i+1) = A'\ X'(i) + B' \quad (\text{modulus } T)$$

where the primed variables are related to those of the original sequence in the following way

$$X'(i+1) = X(i+k), \quad A' = A^k \ (\text{modulo } T), \text{ and}$$
$$B' = [(A^k-1)/(A-1)]*B \ (\text{modulo } T):$$

$$X(i+k) = A^k*X(i) + [(A^k-1)/(A-1)]*B \quad (\text{modulo } T)$$

The values of A' satisfy the specification that A' (modulo 4) = 1, but B' is not necessarily odd. Since we are not assured that such sequences are statistically acceptable, this may not be the proper method.

METHOD TWO -- WORK ON ALL RANDOM VARIABLES AT ONCE

A more defensible way to calculate a series of factor of safety figures may be to calculate and store a reasonably large number, v, of random values for each random variable, and calculate corresponding factors of safety for each of v trials, as indicated in Table 3.

Random Variable	trial 1	trial 2	trial 3	...
tree surcharge	X0	X1	X2	...
slope	Xv	Xv+1	Xv+2	...
soil cohesion	X2v	X2v+1	X2v+2	...
soil depth	X3v	X3v+1	X3v+2	...
soil density sat.	X4v	X4v+1	X4v+2	...
soil density dry	X5v	X5v+1	X5v+2	...

Table 3. Possible order in which variables are assigned values from pseudo-random number sequence {Xi}

With this method, each random variable's values would be based on a consecutive sequence of psuedo-random numbers from URAN. The resulting values for each variable may appear more uniform and/or more random than would those resulting from the first method.

If the computer's storage capacity will not handle the total required number of random values to be stored for each random variable, a smaller number of values for each variable could be calculated and corresponding factors of safety determined, with the whole thing repeated the proper number of times. For instance, if the desired total number of trials is 500, we could perhaps store 50 values for each random variable, calculate fifty factors of safety, and repeat the process nine times.

=====================

-- Starting "seed" (X0) values other than 76293 94531 25 have not been fully tested with $T=2^{47}$, $A=2^{9}+1$, and B=29741 09625 8473 (those values used in URAN), so we do not know how the sequences of pseudo-random numbers generated with other seeds behave, but they should be fairly good most of the time.

-- Don't know how consecutive subsequences of the original sequence from the "proven" seed value behave.

-- Don't know how every k^{th} number from the original sequence behave.

REFERENCES

[1] Huntsberger, D.V.; "Elements of Statistical Inference," Allyn and Bacon, 1967.

[2] Devore, J.L.; "Probability & Statistics for Engineering and the Sciences," Brooks/Cole, 1982.

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[4] Abramowitz, M. and I.A. Stegun, ed.; "The Handbook of Mathematical Functions", Chapter 20, "Probability Functions" by M. Zelan and N.C. Severo, Dover, 1965

[5] Hull, T.E. and A.R. Dobell; "Random Number Generators," Soc. for Ind. and App. Mathematics Review, v. 4 no. 3, July 1962.

Item 9

LEVEL 3 MODIFICATIONS

I IMPLEMENTATIONAL

A. ADDED GRAPHICS SUBROUTINES TO EMULATE CALCOMP ROUTINES: PLOT, PLOTS, NUMBER, SYMBOL, AXIS with sub-functions STSYM, SPSYM, SAXIS.

We added a number of routines to emulate the CALCOMP routines PLOT, PLOTS, NUMBER, SYMBOL (both "special" and "standard"), and AXIS as called by STABL3. They are not all full implementations of the corresponding CALCOMP routines.

1) DATA TO FILE FOR SUBSEQUENT PLOT ON PLOTTER OR SCREEN

These routines write to a disk file the required data for each routine, for subsequent use by a graphics program. We have developed two programs to read the plot file and plot to either the PC screen or a Houston Instruments DM/PL pen plotter. We have also developed a method to import the data for use by the GOLDEN software series for nice plots on dot matrix printers.

2) DESCRIPTION OF GRAPHICS SYSTEM

+) FILE FORMAT

The plot file is a sequential ASCII file with values within records separated by commas. The file is composed of a number of "entries", one for each call to PLOT, AXIS, SYMBOL, or NUMBER. Each entry consists of a record with an entry code followed by an X and a Y value. Some of the entries will have a second record with data specific to that plot command.

The supported CALCOMP routines, and their respective entry codes used in the plot file, are defined below. The actual format and description of parameters stored are given under the individual subroutine descriptions.

PLOTS	--	Opens plot file. No data generated.
PLOT	--	Code 1 (for IPEN = +/- 2)
		Code 2 (for IPEN = +/- 3)
NUMBER	--	Code 3. Two records.
SYMBOL	--	Code 4 (special symbol). Two records.
		Code 5 (standard symbol). Two records.
AXIS	--	Code 6. Two records.

+) PLOTDMP

Program written in BASIC to read the plot file and generate the specified plot on a pen plotter supporting the Houston Instruments DM/PL command set.

+) PEAGLE

Program written in BASIC to read the plot file and generate the specified plot on a PC graphics screen.

+) GOLDEN SOFTWARE LINK

The plot file can also be rearranged slightly to match the formatting requirements for input files to the GOLDEN software products, which create nice plots on a dot matrix printer (such as the Epson).

3) SUBROUTINE DESCRIPTIONS

Each CALCOMP emulation routine is briefly described here, including a description of the data format used in the plot file.

+) PLOTS(IBUF,NLOC,LDEV)
Opens plot file to receive commands from subsequent calls to CALCOMP emulation routines. The user is asked for a file name to be used (default TEMPPLOT); maximum length of file name is 21 characters. File must not already exist. The file is opened as unit 13. IBUF, NLOC, and LDEV are not used, and are ignored. No output to the file is generated.

+) PLOT(XPAGE,YPAGE,IPEN)
If IPEN = 999 then the plot file is closed, and a message to that effect is printed on the screen.
If IPEN = 2 or -2, write to file

```
   1, XPAGE, YPAGE                      [I2 , F10.2 , F10.2]
```

If IPEN = 3 or -3, write to file

```
   2, XPAGE, YPAGE                      [I2 , F10.2 , F10.2]
```

Note that negative values of IPEN are not currently differentiated from their positive counterparts.

+) NUMBER(XPAGE,YPAGE,HT,FPN,ANGLE,NDEC)
Write to file:

```
   3, XPAGE, YPAGE                      [I2 , F10.2 , F10.2]
   HT, FPN, ANGLE, NDEC          [F8.2 , F12.6 , F8.3 , I3]
```

+) SYMBOL(X,Y,HT,IBCD,ANGLE,NCH)
SYMBOL(X,Y,INTEQ,ANGLE,ICODE)

Special or standard symbol plot. Standard symbol (NCH/ICODE less than zero) has maximum text length of 50 characters, and is assumed to be passed in A4 chunks. Write to file:

```
   4, X, Y                              [I2 , F10.2 , F10.2]
   HT, INTEQ, ANGLE, ICODE          [F8.2 , I3 , F8.3 , I3]
   5, X, Y                              [I2 , F10.2 , F10.2]
   HT, ANGLE, NCH, STRING   [F8.2 , F8.3 , I3 , "---------"]
```

+) AXIS(XPAGE,YPAGE,TITLE,NCH,AXLEN,ANGLE,FIRSTV,DELTAV,
R1,I1,I2,I3,R2)

Generate an axis, with a title (maximum 50 characters, in A4 variables). CALCOMP specifies that the sign of NCH specifies which side of the axis line the title is to appear. We honor this for the call to AXIS, but within the plot file, we make NCH positive, and use the sign of AXLEN to specify this. Also, some versions of the CALCOMP manuals say nothing about the last 5 arguments, but STABL3 uses them, so we pass them on and store them in the plot file. Writes to file:

```
6, XPAGE, YPAGE                              [I2 , F10.2 , F10.2]
NCH, AXLE, ANGLE, FIRSTV, DELTAV, R1,I1,I2,I3,R2, TITLE

   [I4,F8.3,F8.3,F8.3,F8.3,F8.3,I3,I3,I3,F8.3,"---------"]
```

B. SOURCE (& OBJECT) CODE BROKEN INTO 14 MANAGEABLE CHUNKS:

```
STABL3   - READER   - QUIT
PROFIL   - (SOIL)
ANISO
WATER    - LOADS    - EQUAKE
LIMITS   - INTSCT   - (INTSC2)
SURFAC   - RANDOM   - (BLOCK)
RANSUF
BLKSUF
SLICES   - SORT     - EXECUT    - BLOCK2
WEIGHT   - SOILWT
FACTR    - [CFJ]
SCALER   - PLOTIN   - (PLOTN2)  - (PLOTN3)
PLTN     - (PLT2)   - (PLT3)    - (PLT4)
         - POSTN    - [URAN]
PLOTTING SUBROUTINES
```

C. ENTRY

1) The mainframe version had ENTRIES into several of the subroutines. Microsoft FORTRAN does not seem to support them, so we changed the program slightly to get around this limitation. The ENTRY points are:

ENTRY POINT(S)	in	SUBROUTINE
SOIL		PROFIL
INTSC2		INTSCT
BLOCK		RANDOM
PLOTN2, PLOTN3, PLOTN4		PLOTIN
PLT2, PLT3, PLT4		PLTN

Subroutines PROFIL, RANDOM, PLOTIN, and PLTN originally had no arguments. We added one argument each, IENTRY, to indicate whether to execute the main routine or to jump to an alternative entry point, as follows:

```
+) PROFIL(IENTRY)
           1  PROFIL
           2  SOIL
   RANDOM(IENTRY)
           1  RANDOM
           2  BLOCK
   PLOTIN(IENTRY)
           1  PLOTIN
           2  PLOTN2
           3  PLOTN3
   PLTN  (IENTRY)
           1  PLTN
           2  PLT2
           3  PLT3
           4  PLT4
```

2) INTSCT already has a long argument list, including a value returned as INTS (the last argument in the list). We chose to set this variable to 1 to specify a call to INTSCT, or a 2 to specify a call to ENTRY INTSC2:

```
   INTSCT(...,INTS)
           1  INTSCT
           2  INTSC2
```

D. URAN random number generator

1) describe
2) listing
3) test overview

E. ERROR CODES, ETC.
The mainframe version used

```
DATA KEYW/6HPROFIL,5HLOADS,5HWATER.../,
```

which gave error messages from the Microsoft compiler when we tried to compile it. These were all converted to

```
KEYW(1)="PROFIL"
KEYW(2)="LOADS"
KEYW(3)="WATER"
etc.
```

F. Array WAR(100) was passed to routine PLOTS. Neither our mainframe nor our PC version support this, and it was deleted.

G. FILE SYSTEM FOR PC

1) FILEIN	: INPUT DATA FILE	UNIT 5	[Opened in MAIN]
2) FILEUT	: OUTPUT FILE	UNIT 6	[Opened in MAIN]
3) FILEN	: PLOT FILE	UNIT 13	[Opened in PLOTS]

H. COMPILER DIRECTIVE $DO66 USED
Use FORTRAN IV convention for do loops (i.e., run through the loop at least once)

II ALGORITHMIC MODIFICATIONS TO PROGRAM STABL3

Three algorithmic changes have been made to STABL3. They are:

- o Very thin slices correction (subroutine WEIGHT),
- o Pore pressure correction (subroutine WEIGHT), and
- o Janbu ~~factor of safety~~ correction factor, Fo (subroutine FACTR).

Each of these modifications is described in detail below. Listings of the modified subroutines WEIGHT and FACTOR (and the added function CFJ) are given in the appendices.

A. MODIFICATION FOR VERY THIN SLICES

STABL3 divides the soil mass into vertical slices at each horizontal coordinate defining

trial failure surface
piezometric surfaces
soil type boundaries
ground surface

and sometimes the resulting slices end up being very thin; too thin to be meaningful for analysis, and thinner than the computer's numerical accuracy can handle. This condition results in an error message being generated from within subroutine WEIGHT:

```
****************************************************
******  INPUT ERROR - TRIAL FAILURE SURFACE   ******
******                EXTENDS ABOVE THE       ******
******                GROUND SURFACE          ******
****************************************************
```

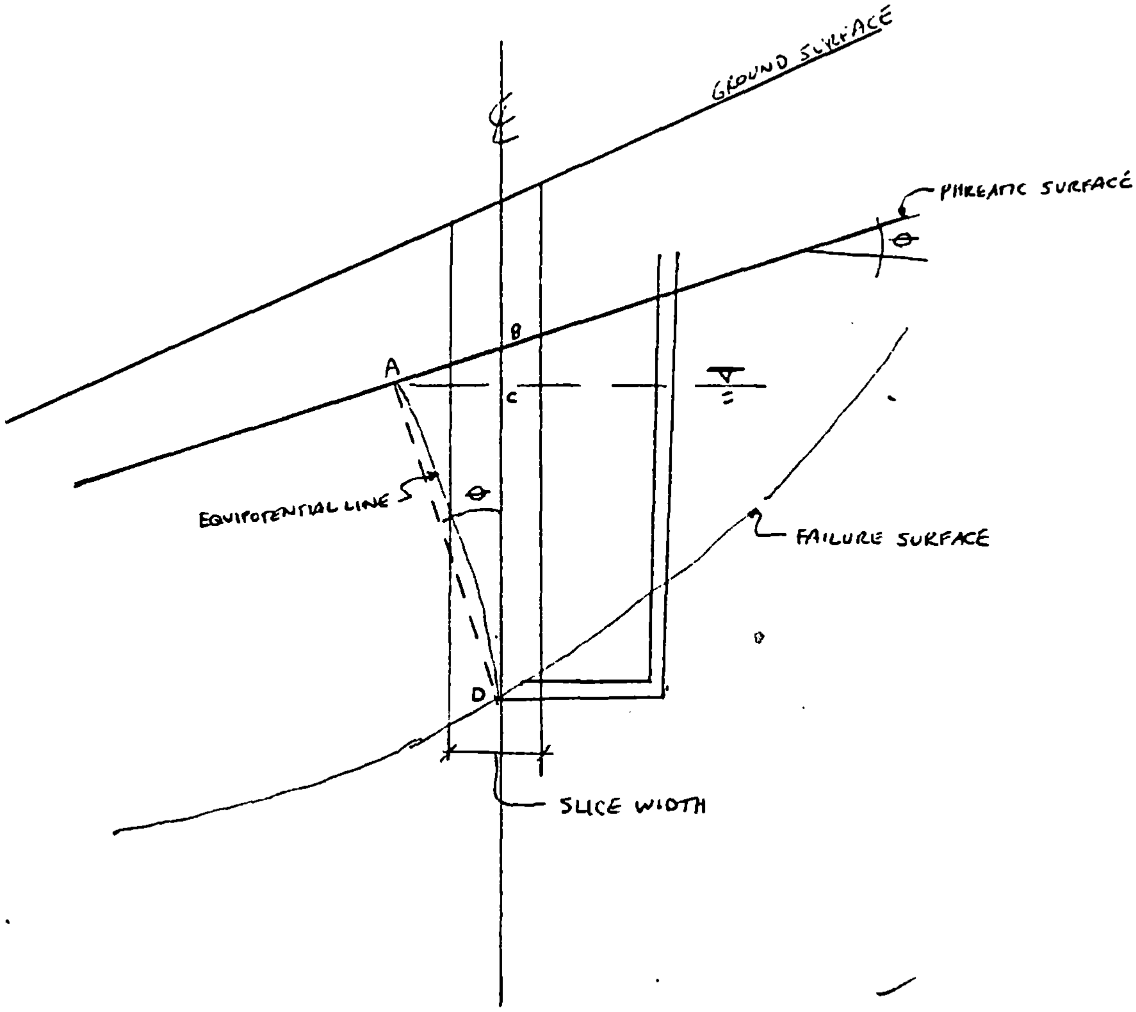
We skip potential slices which are so thin that the top of the slice, YT, is not found to be higher than the bottom of the slice, YB. One statement, marked DH010585, is modified in subroutine WEIGHT.

```
    --
    --
 C
 C  ----------------------------------------
 C  DETERMINE BASE OF SLICE AND ITS INCLINATION
 C  ----------------------------------------
 C
      DO 4 J=JB,NSURF
    --
    --
*     IF (INTS.EQ.1 .AND.YT.GT.YB ) GOTO 6
                         =============          THIS PART ADDED...
   4  CONTINUE
   6  ...
```

Note another potential problem: for the DO 3, DO 4, and DO 7 loops, you jump out of the loop if an intersection is found (if INTS=1), or drop out of the loop if no intersection is found. There is no check to ensure that a valid intersection was found.

B. PORE PRESSURE CORRECTION, Kw.

For steady-state flow, the piezometric surface for any point will rise to the level where the equipotential passing this point intersects the phreatic surface.



If the phreatic surface slopes, an error $\overline{BC}$ is introduced; that is, the program uses $\overline{BD}$ when it should use $\overline{CD}$.

If θ is the angle of the phreatic surface, then the error $\overline{BC}$ is

$$\overline{BC} = \overline{AB} \sin \theta$$
$$\overline{BC} = (\overline{BD} \sin \theta) \sin \theta$$
$$\overline{BC} = \overline{BD} \sin^2 \theta$$

and the correct pore pressure is

$$u = \overline{BD} (1-\sin^2 \theta)$$

In the unmodified STABL3, we have for each slice "I":

IF (YW(K) > YB) [THAT IS, IF THE PHREATIC SURFACE IN QUESTION IS WITHIN THE SOIL SLICE]

THEN

```
UALPHA(I) = (YW(K)-YB) * 62.4 * DX(I) / COS (ALPHA)
```

which is equivalent to $UALPHA = \frac{BD \cdot 62.4 \cdot DX}{COS\ (ALPHA)}$

which is incorrect for a sloping phreatic surface. The formula for UALPHA is modified as follows:

$$UALPHA = \frac{BD\ (1-SIN^2\ \theta) \cdot 62.4 \cdot DX}{COS\ (ALPHA)}$$

Using the notation in the following figure (and that used in the program), we have:

```
IN2 = NP(SOIL(K))
IN1 = JW(IN2)
XX1 = XPIEZ(IN2,IN1-1)
XX2 = XPIEZ(IN2,IN1)
YY1 = YPIEZ(IN2,IN1-1)
YY2 = YPIEZ(IN2,IN1)
THETA = ATAN((YY2-YY1)/(XX2-XX1))
STHETA = SIN(THETA)
THETAC = (1-SIN^2 (THETA))
UALPHA(I) = THETAC * (YW(K)-YB) * UWAT * DX(I) / CA
```

ALPHA	ANGLE OF BASE OF THE SLICE
CA	COSINE OF ANGLE ALPHA
DX	WIDTH OF THE SLICE
JW	ARRAY CONTAINING SUBSCRIPT OF LAST POINT DEFINING EACH PIEZOMETRIC SURFACE, USED TO DETERMINE THE INTERSECTION OF THE CENTERLINE OF A SLICE WITH THE PIEZOMETRIC SURFACE.
NP	ARRAY CONTAINING NUMBER OF PIEZOMETRIC SURFACE FOR EACH SOIL TYPE.
SOIL	ARRAY CONTAINING INDICES OF THE SOIL TYPE OF EACH SUBSECTION WITHIN A SLICE.
STHETA	SINE OF THE ANGLE THETA
THETA	ANGLE OF PHREATIC SURFACE
THETAC	CORRECTION FACTOR TO BE USED: $1-SIN^2(THETA)$
UALPHA	HYDROSTATIC FORCE ACTING AT THE BASE OF THE SLICE
UWAT	UNIT WEIGHT OF WATER
XPIEZ	ARRAY CONTAINING X COORDINATES OF POINTS DEFINING WATER SURFACE.
YPIEZ	ARRAY CONTAINING Y COORDINATES OF POINTS DEFINING WATER SURFACE.
YW	ARRAY CONTAINING Y COORDINATE OF THE PIEZOMETRIC SURFACE FOR EACH SOIL TYPE OF A ~~SOIL~~. SLICE.

YW is a reordering of Y such that YW(K) = Y(NP(SOIL(K)))

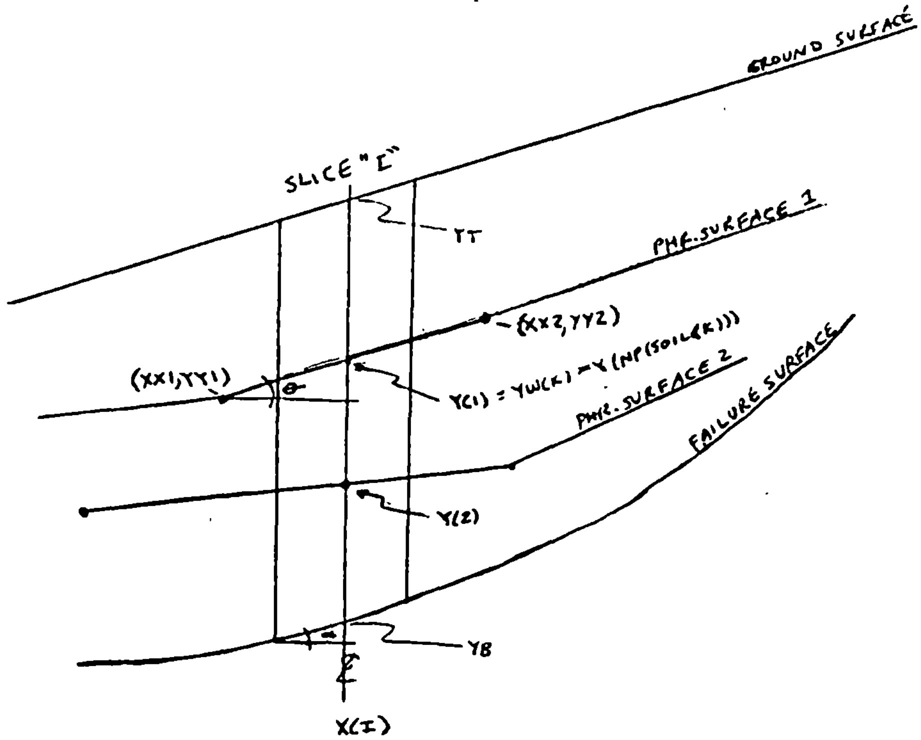


Figure: (dh)

(XX1,YY1) = (XPIEZ(NP(SOIL(K)), JW(NP(SOIL(K)))-1),
YPIEZ(NP(SOIL(K)), JW(NP(SOIL(K)))-1))
(XX2,YY2) = (XPIEZ(NP(SOIL(K)), JW(NP(SOIL(K)))),
YPIEZ(NP(SOIL(K)), JW(NP(SOIL(K)))))

The modifications can be found in subroutine WEIGHT, marked with DH090485, and fit into the scheme of the subroutine as follows:

```
    DO 2 I=1,NSLICE                                  (FOR EACH SLICE)
    -
    -
C
C   DETERMINE POSITION OF WATER TABLE FOR ALL SOILS IF PRESENT
C
          DO 25 N=1,NPZ                              (FOR EACH PHR. SURFACE)
             -
             -
 25       -
                         --------------------------
                          PORE PRESSURE CORRECTIONS
                         --------------------------
  2 -
```

** NOTE -- if there is more than one phreatic surface, then the results are not guaranteed. Only the "last" phreatic surface is used in the correction. Further work is necessary to separate, within the program, the difference between phreatic surface and piezometric surface.

C. JANBU FACTOR OF SAFETY CORRECTION FACTOR Fo

EXPLANATION OF THE NEED FOR THE CORRECTION FACTOR

need FS = Fo * F

where F is the factor of safety calculated without the correction factor, and FS is the corrected factor of safety.

We have added a function CFJ (Correction Factor Janbu) which returns to subroutine FACTR the required correction factor Fo for the trial failure surface. Fo is ~~be~~ defined as

$$Fo = 1 + k * [(D/L) - 1.4 * (D/L)^2]$$

where

k = 0.31 for cohesionless soils
  = 0.50 otherwise,

which presents a problem, since we may have some of each type of soil in a particular problem. For the first cut, we simply use k=0.31 if the majority of slices are of cohesionless soil; otherwise we use k=0.50. To do this, we count the number of slices for which C=0, and pass this (NC0) and the total number of slices (NSLICE) to CFJ. The geometry of the trial failure surface is also passed to CFJ, in common BLK05.

The factor of safety for the trial failure surface is calculated in FACTR by an iterative process, until

1. FS converges (successive iterations differ by less than 0.005), or
2. 10 iterations without sufficient convergence.

We calculate Fo for each iteration, and apply the correction factor as we go. However, Fo does not change between iterations, and so should not affect convergence for the factor of safety figure*. It would be more efficient to either

1. calculate the correction factor once before we start the convergence iterations, and apply the factor each time, or
2. converge upon a non-corrected factor of safety figure, and then calculate and apply the correction factor Fo.

These modifications are in subroutine FACTR and are marked 051486DH. Function CFJ was also added. These are listed in the appendices.

----

* The convergence tolerence will effectively be changed, but only very slightly, since Fo can be expected to be about 1.02 to 1.06.

MODIFICATION SCHEME FOR JANBU CORRECTION -- SUBROUTINE FACTR

```
      -
      -
      SUMB=0.0
*     NCO=0
*C  NCO IS NUMBER OF SLICES WITH COHESIONLESS SOIL
 C
 C  --------------------------------
 C  CALCULATE REQUIRED ANGLE FUNCTIONS
 C  --------------------------------
 C
      DO 2 I=1,NSLICE
         -
         -
         IF (MB.EQ.1) GOTO 40              (IF BISHOP)
*C
*C  COUNT NUMBER OF SLICES FOR WHICH C=0
*C
*        IF (CSLICE.LE.0.01) NCO=NCO+1     (OR VERY CLOSE TO 0)
 C
 C  SIMPLIFIED JANBU A-TERMS
 C
         -
         -
  2   CONTINUE
      -
      -
      DO 10 J=1,10                         (SAFETY FACTOR ITERATION)
*C
*C  -----------------------------------------------
*C  CALCULATE CORRECTION FACTOR FOR JANBU CALCULATION
*C  -----------------------------------------------
*C
*        F0=1.0                            (ASSUME Fo IS 1.0 IN CASE
                                           BISHOP'S IS BEING USED)
*        IF (MB.NE.1) F0=CFJ(NCO,NSLICE)   (IF JANBU, CALCULATE
                                           CORRECTION FACTOR Fo)
*C
*        FNEW = F0 * SUMT/SUMB             (WAS: FNEW=SUMT/SUMB)
 C
 C  --------------------
 C  CHECK FOR CONVERGENCE
 C  --------------------
 C
         IF (ABS(FNEW-FOLD).LT..005) GOTO 15   (IF FS CONVERGES WITHIN 10
                                               ITERATIONS, RETURN)
 10   FOLD=FNEW
      -
      -
 15   FS=FNEW                              (PERHAPS SHOULD CALL CFJ
                                           HERE:
      -                                    15 F0=1.0
      -                                       IF (MB.NE.1)F0=CFJ()
                                              FS = F0 * FNEW
```

C. CONTINUED...

FUNCTION CFJ(NCO,NSLICE)

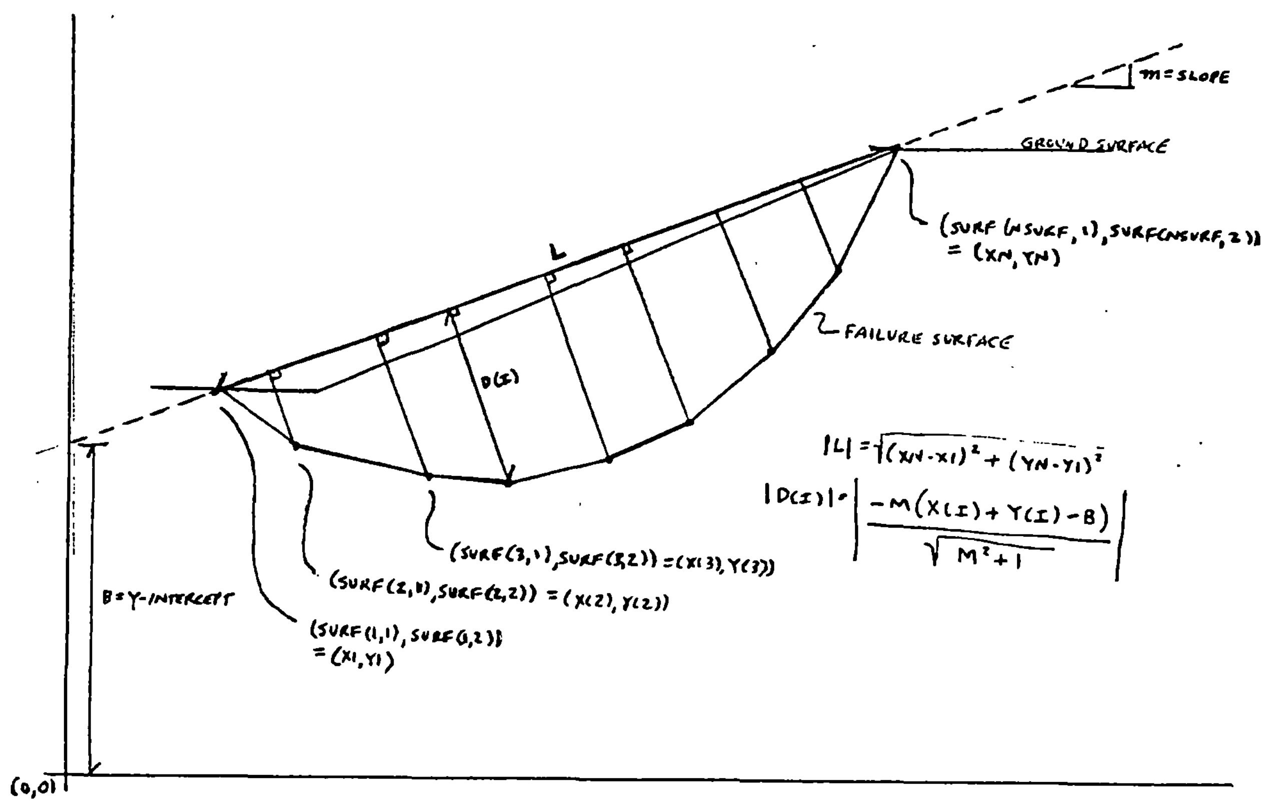
RETURNS JANBU CORRECTION FACTOR FOR THE TRIAL FAILURE SURFACE GIVEN THE FAILURE SURFACE GEOMETRY (IN COMMON BLK05); THE NUMBER OF SLICES REPRESENTING COHESIONLESS SOILS, AND THE TOTAL NUMBER OF SLICES (PASSED AS ARGUMENTS).

Calculate and return $Fo = 1 + k * [(D/L) - 1.4 * (D/L)^2]$

where k, D, and L are defined as follows:

- o k = 0.31 for cohesionless soils (C=0)
  = 0.50 otherwise (C > 0 and PHI > 0)
  Since different slices can have different values for soil cohesion, we had to decide upon an appropriate value for <u>k</u> for the overall problem. For this version, we use either 0.31 or 0.50 depending upon the ratio of cohesionless slices to the total number of slices. If this ratio is greater or equal to 1/2, then we use k=0.31. An alternative approach would be to use a sliding <u>k</u> value depending upon the relative size of the ratio NCO/NSLICE.
- o L = length of cord L in figure =========
- o D = length of longest cord D in figure =========
  (the D's are cords between trial failure surface coordinates and cord L such that they intersect L at a right angle)

Function listing in the appendix.



```
$D066
      SUBROUTINE WEIGHT
C   ------------------------------------------------------------------STA53920
C   ------------------------------------------------------------------
C                            SUBROUTINE WEIGHT
C   ------------------------------------------------------------------
C   ------------------------------------------------------------------
C
C   FUNCTIONS -
C
C        DETERMINES THE INCLINATION OF THE TOP AND BOTTOM OF EACH
C        SLICE.
C
C        DETERMINES THE RESULTANT WATER FORCES AT THE TOP AND BASE OF
C        EACH SLICE IF PRESENT.
C
C        DETERMINES THE TOTAL WEIGHT OF EACH SLICE AND THE SOIL TYPE AT
C        THE BASE OF EACH SLICE.
C
C        DETERMINES THE SURCHARGE FORCE, IF ANY, AT THE TOP OF EACH
C        SLICE.
C
C   MODIFIED JAN 15, 1985     DAVID HALL                             DH011585
C        FIX FOR SLICES OF MICROSCOPIC WIDTH                          DH011585
C
C   MODIFIED SEP 04, 1985     DAVID HALL & PAUL SWETIK               DH090485
C        PORE PRESSURE CORRECTION                                     DH090485
C
C   ------------------------------------------------------------------
C   ------------------------------------------------------------------
C
      COMMON /BLK01/IANGL,IBLK,IEXIT,ICIRC,ILIMIT,IPLOT,IREAD,ISEARC,
     1        IBLK2,ISOIL,ISTR,ISURC,ISURF,IWAT,RD,TOL
      COMMON /BLK02/BNDS(100,4),C(20),GAMMA(20),GSAT(20),ITP(100),NBND,
     1              NSOIL,NTOP,PHI(20),RU(20),CU(20),NP(20)
      COMMON /BLK03/UWAT,NPZ,NPIEZ(10),XPIEZ(10,40),YPIEZ(10,40)
      COMMON /BLK04/DELTA(10),LOAD(10),NSURC,SURC(10,2),YSURC(10,2)
      COMMON /BLK05/NSURF,SURF(100,2)
      COMMON /BLK08/NSLICE,X(300)
      COMMON /BLK09/ALPHA(200),BETA(200),DX(200),SLTP(200),UALPHA(200),
     1              UBETA(200),WTT(200)
      COMMON /BLK10/DELT(200),P(200)
      COMMON /BLK11/CAVT,KCOEF,VKCOEF
      COMMON /BLK15/M,MB
      COMMON /BLK21/HIGHT(200),HGHTEQ(200)
      DIMENSION YI(20),YW(20),JW(10),Y(10)
      REAL KCOEF,LOAD
      INTEGER SOIL(20),SOILTP,SLTP
      JT=1
      JB=2
      JS=1
      IF (NPZ.EQ.0) GO TO 110
      DO 13 J=1,NPZ
```

```
      JW(J)=2
   13 CONTINUE
110   CONTINUE
      NTOP1=NTOP+1
C
C   ------------------------------------------                          STA56470
C   CALCULATE THICKNESS AND MIDPOINT OF SLICE
C   ------------------------------------------
C
      DO 2 I=1,NSLICE
C
C     INITIALIZE THE SLICE HEIGHT AND THE HEIGHT OF THE CENTROID OF     DH072886
C     THE EARTHQUAKE FORCE ABOVE THE BASE OF THE SLICE
C
      HIGHT(I) = 0.0
      HGHTEQ(I) = 0.0
      DX(I)=X(I+1)-X(I)
      X(I)=(X(I)+X(I+1))/2.
      DO 16 J=1,NSOIL
      YW(J)=0.
   16 CONTINUE
C
C   ------------------------------------------                          STA56640
C   DETERMINE TOP OF SLICE AND ITS INCLINATION
C   ------------------------------------------
C
      DO 3 J=JT,NTOP
      JTN=J
      INTS=2
      CALL INTSCT(BNDS(J,1),BNDS(J,2),BNDS(J,3),BNDS(J,4),0.,0.,0.,0.,
     1   X(I),YT,INTS)
      IF(INTS.EQ.1)GO TO 5
    3 CONTINUE
    5 JT=JTN
      J=JTN
      BETA(I)=ATAN((BNDS(J,2)-BNDS(J,4))/(BNDS(J,1)-BNDS(J,3)))
C
C   -------------------------------------------
C   DETERMINE BASE OF SLICE AND ITS INCLINATION
C   -------------------------------------------
C
      DO 4 J=JB,NSURF
      JTN=J
      INTS=2
      CALL INTSCT(SURF(J-1,1),SURF(J-1,2),SURF(J,1),SURF(J,2),0.,0.,0.,
     1   0.,X(I),YB,INTS)
C
      IF(INTS.EQ.1.AND.YT.GT.YB)GO TO 6                                 DH011585
    4 CONTINUE
    6 JB=JTN
      J=JTN
      ALPHA(I)=ATAN((SURF(J-1,2)-SURF(J,2))/(SURF(J-1,1)-SURF(J,1)))
      CA=COS(ALPHA(I))
```

```
C
C   --------------------------------------------------
C   CHECK IF TRIAL SURFACE IS BELOW THE GROUND SURFACE
C   --------------------------------------------------
C
      IF(YT.GT.YB)GO TO 18
      WRITE(6,101)
  101 FORMAT(//,
     110X'****************************************************'/        STA57000
     110X'******  INPUT ERROR - TRIAL FAILURE SURFACE  ******'/
     110X'******                EXTENDS ABOVE THE      ******'/
     110X'******                GROUND SURFACE         ******'/
     110X'****************************************************'/)
      KEY= 72
      WRITE(6,72)KEY,I,X(I),YT,YB,DX(I)
   72 FORMAT(/,'  XXX KEY=',I4,'  XXX ',I10,5F15.5)
      IF(ISEARC.EQ.0)GO TO 22
      WRITE(6,104)NSURF
  104 FORMAT(///,
     110X,'THE TRIAL FAILURE SURFACE IN QUESTION IS DEFINED',/,
     110X,'BY THE FOLLOWING',I3,
     1    ' COORDINATE POINTS',///,
     1    12X,'POINT',6X,'X-SURF',6X,'Y-SURF',/
     1    13X,'NO.',8X,'(FT)',8X,'(FT)',/)
      WRITE(6,105)(J,SURF(J,1),SURF(J,2),J=1,NSURF)
  105 FORMAT(12X,I3,2X,2F12.2)
   22 CALL PLTN(4)
      CALL QUIT
   18 K=1
      SOIL(1)=ITP(JT)
      IF(NTOP.EQ.NBND)GO TO 12
C
C   --------------------------------------------------
C   DETERMINE POSITIONS OF SOIL TYPE INTERFACES, IF ANY
C   AND DETERMINE SOIL TYPE AT BASE OF SLICE.
C   --------------------------------------------------
C
      DO 9 J=NTOP1,NBND
      INTS=2
      CALL INTSCT(BNDS(J,1),BNDS(J,2),BNDS(J,3),BNDS(J,4),0.,0.,0.,0.,
     1   X(I),YI(K),INTS)
      IF(INTS.NE.1)GO TO 9
      IF(YI(K).LE.YB)GO TO 12
      K=K+1
      SOIL(K)=ITP(J)
    9 CONTINUE
   12 SLTP(I)=SOIL(K)
      SOILTP=SLTP(I)
      UALPHA(I)=0.
      UBETA(I)=0.
      IF(IWAT.EQ.0)GO TO 10
C
C   ------------------------------------------------------------       STA57430
```

```
C   DETERMINE POSITION OF WATER TABLE FOR ALL SOILS IF PRESENT
C   ------------------------------------------------------------
C
      DO 25 N=1,NPZ
      JJ=JW(N)
      NN=NPIEZ(N)
      DO 7 J=JJ,NN
      JTN=J
      INTS=2
      CALL INTSCT(XPIEZ(N,J-1),YPIEZ(N,J-1),XPIEZ(N,J),YPIEZ(N,J),
     1   0.,0.,0.,0.,X(I),Y(N),INTS)
      IF(INTS.EQ.1)GO TO 8
    7 CONTINUE
    8 JW(N)=JTN
   25 CONTINUE
      DO 26 J=1,K
      YW(J)=Y(NP(SOIL(J)))
   26 CONTINUE
C                                                                       DH090485
      IN2=NP(SOIL(K))                                                   DH090485
      IN1=JW(IN2)                                                       DH090485
      THETA=ATAN((YPIEZ(IN2,IN1)-YPIEZ(IN2,IN1-1))/(XPIEZ(IN2,IN1)-     DH090485
     $  XPIEZ(IN2,IN1-1)))                                              DH090485
      STHETA=SIN(THETA)                                                 DH090485
      THETAC=1-STHETA*STHETA                                            DH090485
C                                                                       DH090485
      IF(YW(K).GT.YB)UALPHA(I)=THETAC*(YW(K)-YB)*UWAT*DX(I)/CA          DH090485
      IF(YW(1).LT.YT)GO TO 10
C
C   ----------------------------------------------------------          STA57640
C   CALCULATE RESULTANT WATER FORCE AT TOP OF SLICE, IF PRESENT
C   ----------------------------------------------------------
C
      UBETA(I)=DX(I)*(YW(1)-YT)*UWAT/COS(BETA(I))
C
C   ------------------------------------------------------
C   CALCULATE SLICE WEIGHT
C   ------------------------------------------------------
C
10    IF (MB.EQ.1) WTHEQ = 0.0
      IF(K.EQ.1)GO TO 14
      CALL SOILWT(YT,YI(1),ITP(JT),YW(1),WTT(I),I)
      IF (MB.EQ.1) WTHEQ = WTHEQ + ((YT + YI(1))/2.0 - YB)*WTT(I)
      GO TO 15
   14 CALL SOILWT(YT,YB,ITP(JT),YW(1),WTT(I),I)
      IF (MB.EQ.1) WTHEQ = WTHEQ + (YT-YB)/2.0*WTT(I)
      GO TO 21
   15 IF(K.EQ.2)GO TO 17
      K1=K-1
      DO 11 J=2,K1
      CALL SOILWT(YI(J-1),YI(J),SOIL(J),YW(J),WT,I)
      IF (MB.EQ.1) WTHEQ = WTHEQ + ((YI(J-1) + YI(J))/2.0 - YB)*WT
      WTT(I)=WTT(I)+WT
```

```
   11 CONTINUE
   17 CALL SOILWT(YI(K-1),YB,SOIL(K),YW(K),WT,I)
      IF (MB.EQ.1) WTHEQ = WTHEQ + (YI(K-1) - YB)/2.0*WT
      WTT(I)=WTT(I)+WT
   21 IF(YW(K).LT.YB.AND.RU(SOILTP).EQ.0..AND.CU(SOILTP).EQ.0.)GO TO 23
      IF(RU(SOILTP).EQ.0..AND.CU(SOILTP).EQ.0.)GO TO 24
      UALPHA(I)=UALPHA(I)+(WTT(I)*RU(SOILTP)+DX(I)*CU(SOILTP))/CA
   24 IF(KCOEF.EQ.0..AND.VKCOEF.EQ.0.)GO TO 23
      UALPHA(I)=UALPHA(I)-WTT(I)*(KCOEF*SIN(ALPHA(I))+VKCOEF*CA)
      IF(UALPHA(I).LT.CAVT)UALPHA(I)=CAVT
   23 P(I)=0.
      DELT(I)=0.
      IF(ISURC.EQ.0)GO TO 120
C
C    -------------------------------------
C    ASSIGN BOUNDARY LOAD TO SLICE, IF ANY
C    -------------------------------------
C
      DO 19 J=JS,NSURC
      JTN=J
      IF(X(I).LT.SURC(J,1))GO TO 20
      IF(X(I).GT.SURC(J,2))GO TO 19
      DELT(I)=DELTA(J)
      P(I)=LOAD(J)*DX(I)
      GO TO 20
   19 CONTINUE
   20 JS=JTN
120   IF (MB.NE.1) GO TO 2
C
C     CALCULATE (1) THE SLICE HEIGHT AND (2) THE HEIGHT OF THE           DH072886
C     CENTROID OF THE HORIZONTAL EARTHQUAKE FORCE COMPONENT ABOVE THE
C     BASE OF THE SLICE
C
      HIGHT(I) = YT - YB
      HGHTEQ(I) = WTHEQ/WTT(I)
    2 CONTINUE
      RETURN
      END
```

```
$D066
      SUBROUTINE FACTR
C     ------------------------------------------------------------------
C     ------------------------------------------------------------------
C                               SUBROUTINE FACTR
C     ------------------------------------------------------------------
C    MODIFIED FOR JANBU CORRECTION FACTOR             5-14-86
C     ------------------------------------------------------------------
C
C     FUNCTIONS -
C
C          CALCULATES A-TERMS FOR FACTOR OF SAFETY CALCULATION.
C
C          CHECKS FOR CONDITION WHEN THE NORMAL FORCE AT THE BASE OF A
C          SLICE IS NEGATIVE.
C
C          CALCULATES FACTOR OF SAFETY WITH NEWTON-RALPHSON ITERATION.
C
C          IF NO CONVERGENCE BY TEN ITERATIONS, SURFACE COORDINATES
C          ARE PRINTED AND LACK OF CONVERGENCE INDICATED.
C
C          PRINTS FACTOR OF SAFETY IF ANALYSIS IS FOR SPECIFIED TRIAL
C          FAILURE SURFACE.
C
C     ------------------------------------------------------------------
C
C     ------------------------------------------------------------------
C
      COMMON /BLK01/IANGL,IBLK,IEXIT,ICIRC,ILIMIT,IPLOT,IREAD,ISEARC,
     1        IBLK2,ISOIL,ISTR,ISURC,ISURF,IWAT,RD,TOL
      COMMON /BLK02/BNDS(100,4),C(20),GAMMA(20),GSAT(20),ITP(100),NBND,
     1              NSOIL,NTOP,PHI(20),RU(20),CU(20),NP(20)
      COMMON /BLK05/NSURF,SURF(100,2)
      COMMON /BLK07/CSA(10,10),DIREC(10,10),ITPA(10),NDIREC(10),NSAL,
     1              PHIA(10,10)
      COMMON /BLK08/NSLICE,X(300)
      COMMON /BLK09/ALPHA(200),BETA(200),DX(200),SLTP(200),UALPHA(200),
     1              UBETA(200),WTT(200)
      COMMON /BLK10/DELT(200),P(200)
      COMMON /BLK11/CAVT,KCOEF,VKCOEF
      COMMON /BLK12/ANGS1,ANGS2,BPT,EPT,FRTYFV,FS,FSS(12),JJ,NSURFS(12),
     1              PERPEN,SURFS(100,2,12),TSURF,YBPT,YEPT,YMIN
      COMMON /BLK15/ M,MB
      COMMON /BLK20/RADIUS
      COMMON /BLK21/HIGHT(200),HGHTEQ(200)
      DIMENSION A1(200),A2(200),A3(200)
      EQUIVALENCE (ALPHA(1),A1(1)), (BETA(1),A2(1)), (DX(1),A3(1))
      INTEGER SLTP,SOILTP
      REAL KCOEF
      F1=0.
      SUMB = 0.0
      NCO=0                                                             051486DH
C     NCO IS NUMBER OF SLICES WITH NON≠C=0 SOIL                         051486DH
```

```
C
C   ----------------------------------
C   CALCULATE REQUIRED ANGLE FUNCTIONS
C   ----------------------------------
C
      DO 2 I=1,NSLICE
      SD=SIN(DELT(I))
      CD=COS(DELT(I))
      SB=SIN(BETA(I))
      CB=COS(BETA(I))
      SA=SIN(ALPHA(I))
      CA=COS(ALPHA(I))
      TA=SA/CA
      SOILTP=SLTP(I)
      TP=TAN(PHI(SOILTP)*RD)
      CSLICE=C(SOILTP)
      IF(ISTR.EQ.0)GO TO 3
      DO 5 J=1,NSAL
      IF(SLTP(I).NE.ITPA(J))GO TO 5
      ND=NDIREC(J)
      IF(ALPHA(I).GE.DIREC(J,1))GO TO 8
      TP=TAN(PHIA(J,1)*RD)
      CSLICE=CSA(J,1)
      GO TO 3
    8 DO 4 K=2,ND
      IF((ALPHA(I).LT.DIREC(J,K-1)).OR.(ALPHA(I).GE.DIREC(J,K)))GO TO 4
      TP=TAN(PHIA(J,K)*RD)
      CSLICE=CSA(J,K)
      GO TO 3
    4 CONTINUE
    5 CONTINUE
C
C   ---------------------------------------------
C   CHECK IF THE DENOMINATOR OF THE EXPRESSION FOR
C   THE EFFECTIVE NORMAL FORCE IS ZERO OR NEGATIVE
C   ---------------------------------------------
C
    3 F=-TA*TP
      IF(F.GT.F1)F1=F
C
C   -----------------------------------------------------------
C   CALCULATE A-TERMS REQUIRED FOR FACTOR OF SAFETY CALCULATION
C   -----------------------------------------------------------
C
      IF (MB.EQ.1) GO TO 40
C                                                                 051486DH
C    COUNT THE NUMBER OF SLICES FOR WHICH C=0                     051486DH
C                                                                 051486DH
      IF(CSLICE.LE.0.01) NCO=NCO+1                                051486DH
C
C     SIMPLIFIED JANBU A-TERMS
C
      A0 = CSLICE*DX(I) + TP*(WTT(I)*(1.0-VKCOEF) - UALPHA(I)*CA
```

```
     1      + UBETA(I)*CB + P(I)*CD)
      A1(I) = A0/CA**2
      A2(I)=WTT(I)*(TA+KCOEF-VKCOEF*TA)+UBETA(I)*(CB*TA-SB)+P(I)*(CD*TA-
     1   SD)
      A3(I)=TA*TP
      SUMB = SUMB + A2(I)
      GO TO 2
C
C     SIMPLIFIED BISHOP A-TERMS
C
40    A1(I) = CSLICE*DX(I)/CA + TP/CA*(WTT(I)*(1.0-VKCOEF) + P(I)*CD +
     1         UBETA(I)*CB - UALPHA(I)*CA)
      A2(I) = TP*TA
      A3(I) = (WTT(I)*(1.0-VKCOEF) + UBETA(I)*CB + P(I)*CD)*SA
      A4 = (UBETA(I)*SB + P(I)*SD)*(CA-HIGHT(I)/RADIUS)
      A5 = KCOEF*WTT(I)*(CA-HGHTEQ(I)/RADIUS)
      SUMB = SUMB + A3(I) - A4 + A5
    2 CONTINUE
C
C   ------------------------------
C   CALCULATE THE FACTOR OF SAFETY
C   ------------------------------
C
      FOLD=1.5
      DO 10 J=1,10
      SUMT=0.
      DO 6 I=1,NSLICE
      IF(A1(I) .LT. 0.0) A1(I)=0.0
      IF (MB.EQ.1) GO TO 50
      SUMT = A1(I)/(1.0 + A3(I)/FOLD) + SUMT
      GO TO 6
50    SUMT = SUMT + A1(I)/(1.0 + A2(I)/FOLD)
    6 CONTINUE
C                                                                       051486DH
C    ------------------------------------------------                   051486DH
C    CALCULATE CORRECTION FACTOR FOR JANBU CALCULATION                  051486DH
C    ------------------------------------------------                   051486DH
C                                                                       051486DH
      F0=1.0                                                            051486DH
      IF(MB.NE.1) F0=CFJ(NCO,NSLICE)                                    051486DH
C                                                                       051486DH
      FNEW= F0 * SUMT/SUMB                                              051486DH
C
C   ---------------------
C   CHECK FOR CONVERGENCE
C   ---------------------
C
      IF (ABS(FNEW-FOLD).LT..005) GO TO 15
   10 FOLD=FNEW
C
C   --------------------------------
C   STATEMENT OF LACK OF CONVERGENCE
C   --------------------------------
```

```
C
      WRITE(6,103)
  103 FORMAT(//,
     110X,'FACTOR OF SAFETY CALCULATION HAS GONE THROUGH TEN ITERATIONS'
     1//)
      FS=FNEW
      FNEW= 500.
      IF(ISEARC.EQ.0) WRITE(6,101)FS
      IF(ISEARC.EQ.0)GO TO 15
      WRITE(6,104)NSURF
  104 FORMAT(///,
     110X,'THE TRIAL FAILURE SURFACE IN QUESTION IS DEFINED',/,
     110X,'BY THE FOLLOWING',I3,
     1    ' COORDINATE POINTS',///,
     1    12X,'POINT',6X,'X-SURF',6X,'Y-SURF',/
     1    13X,'NO.',8X,'(FT)',8X,'(FT)',/)
      WRITE(6,105)(I,SURF(I,1),SURF(I,2),I=1,NSURF)
  105 FORMAT(12X,I3,2X,2F12.2)
      WRITE(6,101)FS
C
C    ----------------------
C    PRINT FACTOR OF SAFETY
C    ----------------------
C
   15 FS=FNEW
      IF(ISEARC.EQ.1)GO TO 7
      WRITE(6,101)FS
  101 FORMAT(////,10X,'FACTOR OF SAFETY FOR THE PRECEDING SPECIFIED',
     1  ' SURFACE =',F7.3)
      IF(MB.EQ.1) WRITE(6,107)
  107 FORMAT(//,10X,'WARNING - FACTOR OF SAFETY IS CALCULATED BY THE ',
     1    'MODIFIED BISHOP',/,20X,'METHOD. THIS METHOD IS VALID ONLY ',
     1    'IF THE FAILURE SURFACE',/,20X,'APPROXIMATES A CIRCLE.')
      IF(FS.GT.F1)RETURN
      WRITE(6,106)
  106 FORMAT(//,
     110X'***  THE ABOVE FACTOR OF SAFETY IS MISLEADING  ***')
      RETURN
    7 IF(FS.GT.F1)RETURN
      WRITE(6,102)NSURF
      WRITE(6,105)(I,SURF(I,1),SURF(I,2),I=1,NSURF)
  102 FORMAT(//,
     110X'THE FACTOR OF SAFETY FOR THE TRIAL FAILURE SURFACE DEFINED'/
     110X'BY THE COORDINATES LISTED BELOW IS MISLEADING.'///
     110X'FAILURE SURFACE DEFINED BY',I3,' COORDINATE POINTS'///
     112X'POINT',6X,'X-SURF',6X,'Y-SURF',/
     113X'NO.',8X,'(FT)',8X,'(FT)',//)
      WRITE(6,101)FS
      FS= 500.
      RETURN
      END
C
C
```

```
C
      FUNCTION CFJ(NCO,NSLICE)
C
C     CALCULATE FO CORRECTION FACTOR TO FACTOR OF SAFETY FOR JANBU
C
C     HALL AND HOWARD, MAY 1986; JULY 1986
C
C     B      -- Y-INTERCEPT OF LINE CONNECTING X1,Y1 AND XN,YN
C     M      -- SLOPE OF LINE CONNECTING X1,Y1 AND XN,YN
C     NCO    -- NUMBER OF SLICES FOR WHICH C=0
C     NSLICE -- NUMBEROF SLICES TOTAL
C     NSURF  -- NUMBER OF POINTS DEFINING A TRIAL FAILURE SURFACE
C     SURF   -- COORDINATES DEFINING THE TRIAL FAILURE SURFACE
C
      COMMON /BLK05/NSURF,SURF(100,2)
      REAL M,K
      D=0
      X1=SURF(1,1)
      XN=SURF(NSURF,1)
      Y1=SURF(1,2)
      YN=SURF(NSURF,2)
      M=(YN-Y1)/(XN-X1)
      B=Y1-M*X1
      A=-M
      C=-B
      DENOM=SQRT(A**2.+1.)
      RATIO=FLOAT(NCO)/FLOAT(NSLICE)
      NS=NSURF-1
C
C     FIND LENGTH OF LONGEST CORD D
C
      DO 10 I=2,NS
          DI=ABS(A*SURF(I,1)+SURF(I,2)+C)/DENOM
   10 D=AMAX1(D,DI)
C
C     FIND LENGTH OF CORD L
C
      L=((XN-X1)**2.+ (YN-Y1)**2.)**0.5
      DOVERL = D/L
C
C     DETERMINE WHETHER TO USE K=0.31 (C = 0)
C       OR K=0.50 (C > 0  AND PHI > 0)
C
      K=0.50
      IF(RATIO.GE.0.5) K=0.31
C
C     AND, FINALLY, THE ANSWER ...
C
      CFJ = 1 + K*(DOVERL - 1.4 * DOVERL**2.0)
C
          WRITE(*,*)' JANBU CORRECTION FACTOR IS: ',CFJ
      RETURN
      END
```

Item 10

LECTURE NOTES

for

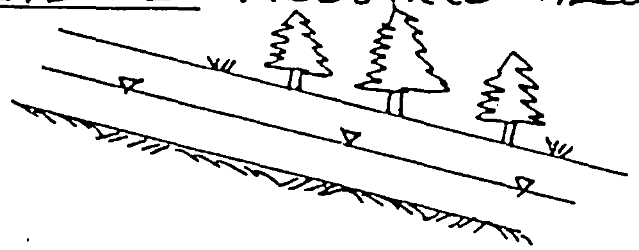
Rod Prellwitz, U.S. Forest Service

and

Terry Howard, University of Idaho

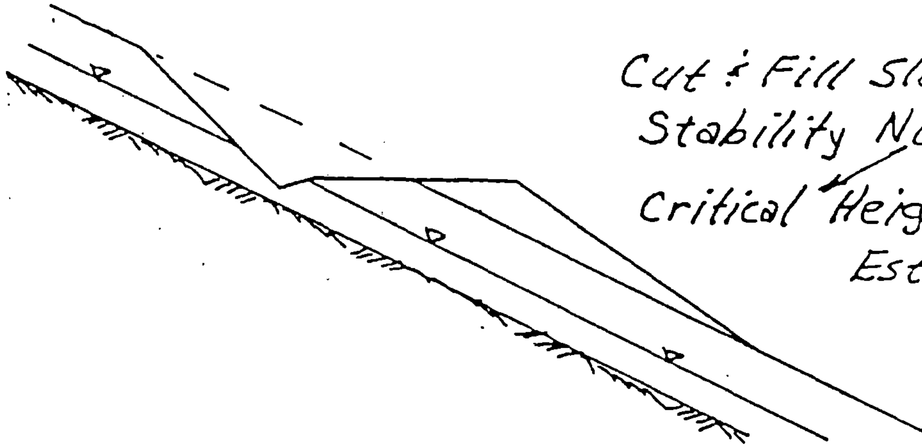
U.S.F.S. RESEARCH - CONCEPT FOR LANDSLIDE HAZARD EVALUATION

LEVEL I - RESOURCE ALLOCATION



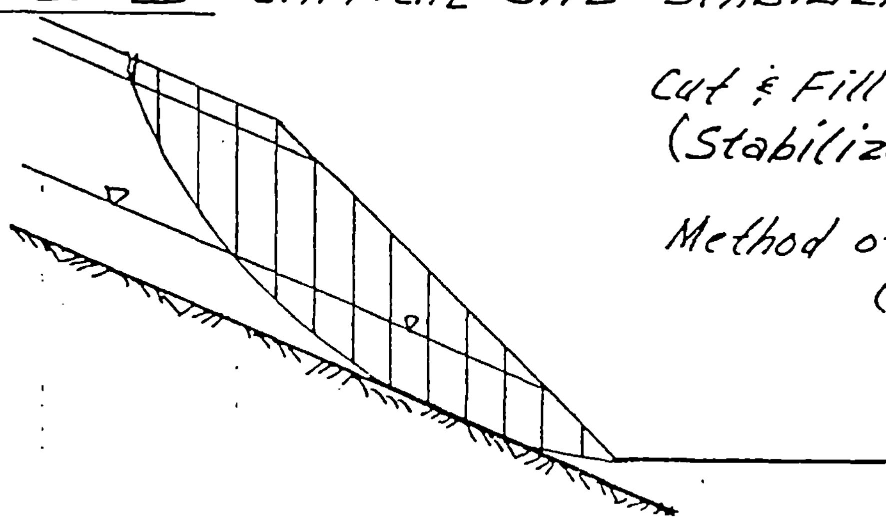
Natural slopes -
Infinite Slope Equation.

LEVEL II - PROJECT PLANNING



Cut & Fill Slopes - (General)
Stability Number Analysis -
Critical Height
Est. Factor of Safety.

LEVEL III - CRITICAL SITE STABILIZATION



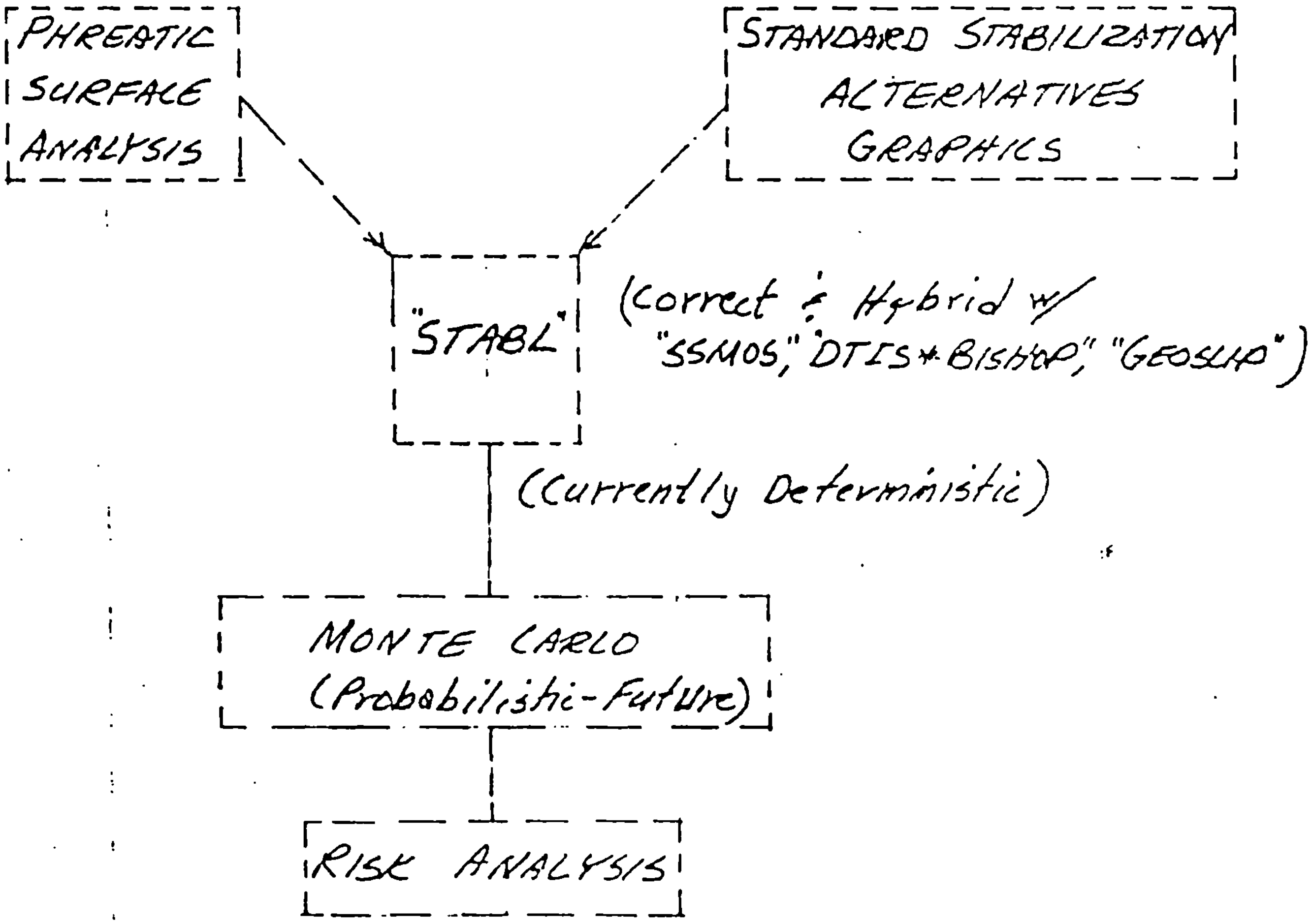
Cut & Fill Slopes - (Specific) -
(Stabilization Alternatives)

Method of Slices Analysis -
(Bishop, Janbu).

LEVEL 3

BISHOP &/or JANBU →

- HP41 - "SSMOS"
- FT. COLLINS - "DTIS & BISHOP" (ICES-LEASE, M.I.T.)
- LOT 7 - "GEOSLIP" (GOLDER)
- MAIN FRAME or IBM-PC - "STABL" (FHWA-PURDUE)



U. ES RESEARCH COMPARISON OF SLOPE STABILITY COMPUTER PROGRAM RESULTS.

CROSS-SECT. No.	BISHOP w/ k_w			BISHOP w/o k_w			JANBU f_o	JANBU w/ f_o & k_w		JANBU w/ f_o	JANBU w/ k_w Only		JANBU w/o f_o & k_w		
	ICES-LEASE	SSMOS	Modif. STABL3	SSMOS	STABL3	PC-STABL4		SSMOS	Modif. STABL3	SSMOS	SSMOS	Modif. STABL3	SSMOS	STABL3	PC-STABL4
1	1.00	1.00	1.01	0.77		0.80	1.05	1.02	1.04	0.80	0.97		0.76		0.77
2	1.00	1.00	1.00	1.00		1.02	1.05	1.02	1.03	1.02	0.97		0.97		0.96
3	1.00	1.01	1.01	0.79		0.83	1.06	1.02	1.01	0.81	0.96	0.93	0.77		0.76
4	1.00	1.01	1.01	0.81		0.91	1.05	1.02	1.02	0.82	0.97	0.95	0.78		0.81
5	1.00	1.01	1.00	0.81		0.82	1.04	1.03	1.02	0.83	0.99		0.80		0.79
6	1.00	1.01	1.00	0.66		0.67	1.04	1.03	1.03	0.68	0.99		0.66		0.65
7	1.00	1.01	1.01	0.77		0.78	1.05	1.00	1.00	0.77	0.95		0.73		0.73
8	1.00	1.00	1.00	0.91		0.99	1.04	1.04	1.04	0.95	1.00		0.91		0.97
9	1.00	1.01	1.01	0.78		0.79	1.06	1.00	1.00	0.78	0.94		0.74		0.73
10	1.00	1.00	1.00	0.93	0.93	0.93	1.06	1.02	1.02	0.95	0.96	0.93	0.89	0.86	0.88
11	1.00	1.00	1.00	0.63		0.65	1.05	1.02	1.03	0.63	0.97		0.60		0.59
12	1.00	1.00	1.00	1.00	1.00	1.01	1.04	1.03	1.03	1.03	0.99	0.97	0.99	0.97	0.98
13	1.00	1.00	1.00	1.00		1.02	1.05	1.01	1.03	1.01	0.96		0.96		0.96

k_w = Phreatic Surface Slope Correction factor = $\alpha_w \cos^2 \alpha_w$

f_o = Janbu's Empirical Correction factor $= 1 + k\left[d/l - 1.4\,(d/l)^2\right]$

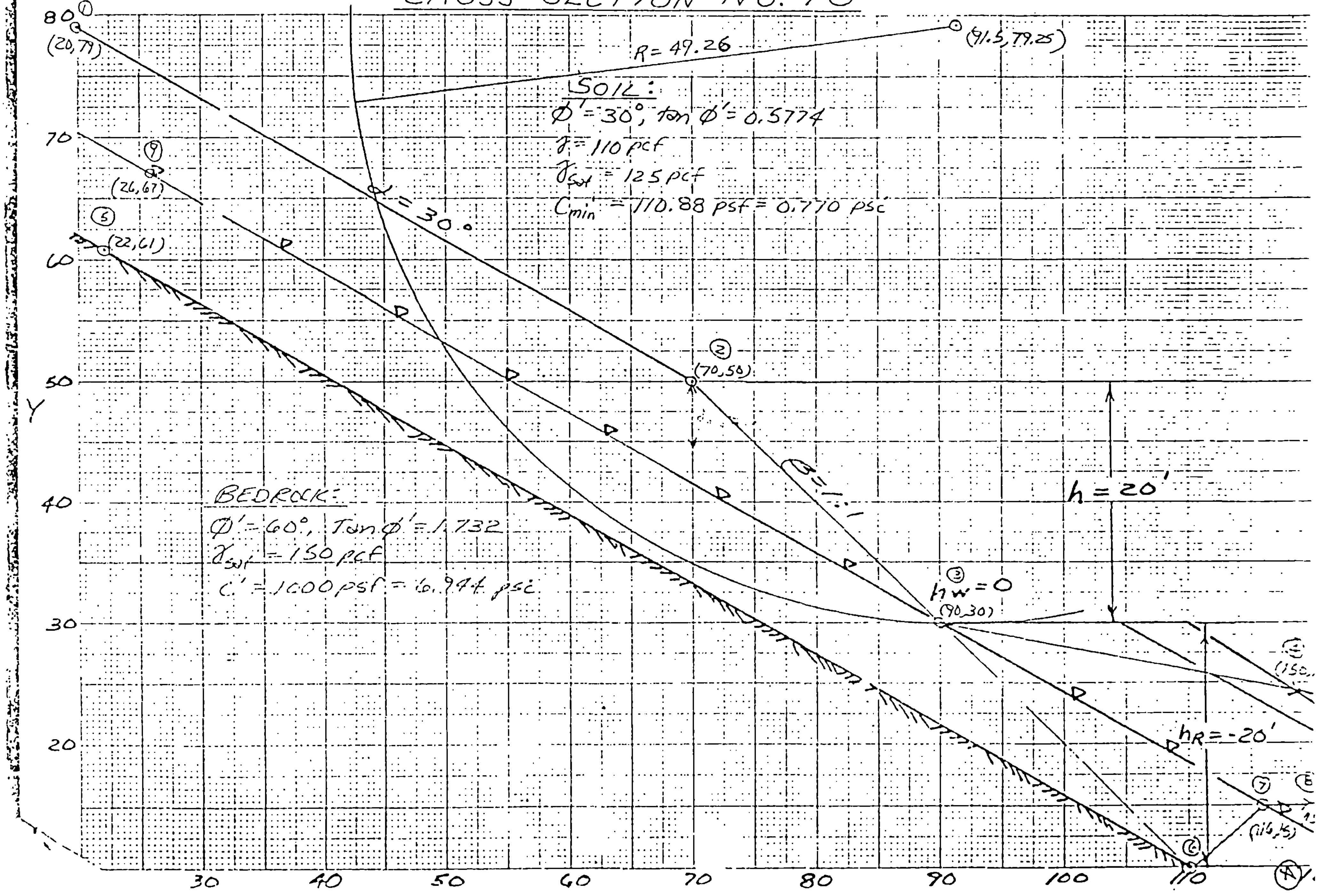
where: $k = 0.31$ for $c = 0$, $\phi > 0$

$k = 0.50$ for $c > 0$, $\phi > 0$

ICES-LEASE = Critical Arc by M.I.T. Program @ Fort Collins C.C. (DTIS*BISHOP).
SSMOS = Solution by U.S.F.S. HP41 Program of ICES-LEASE Critical Arc.
STABL3 = Solution by U. of Idaho PC Version of FHWA-Purdue U. Program before and after k_w and f_o Modification using Critical Arc from Random Search around ICES-LEASE Arc.
PC STABL4 = Solution by Rick Jordon, Olympic NF using FHWA-Purdue U. Program (Unmodified) of ICES-LEASE Critical Arc.

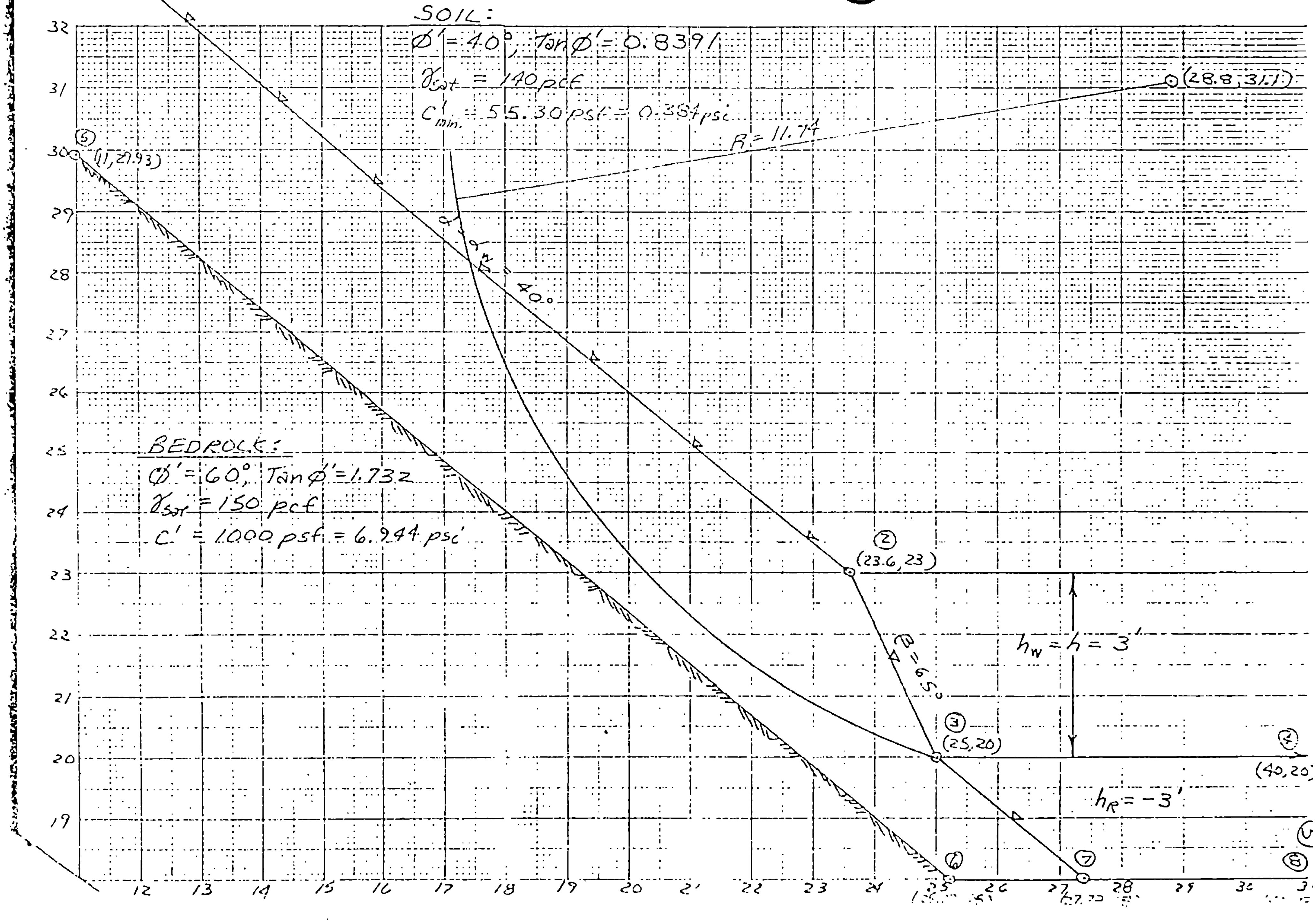
(10)

CROSS SECTION NO. 10



CROSS SECTION No. 11

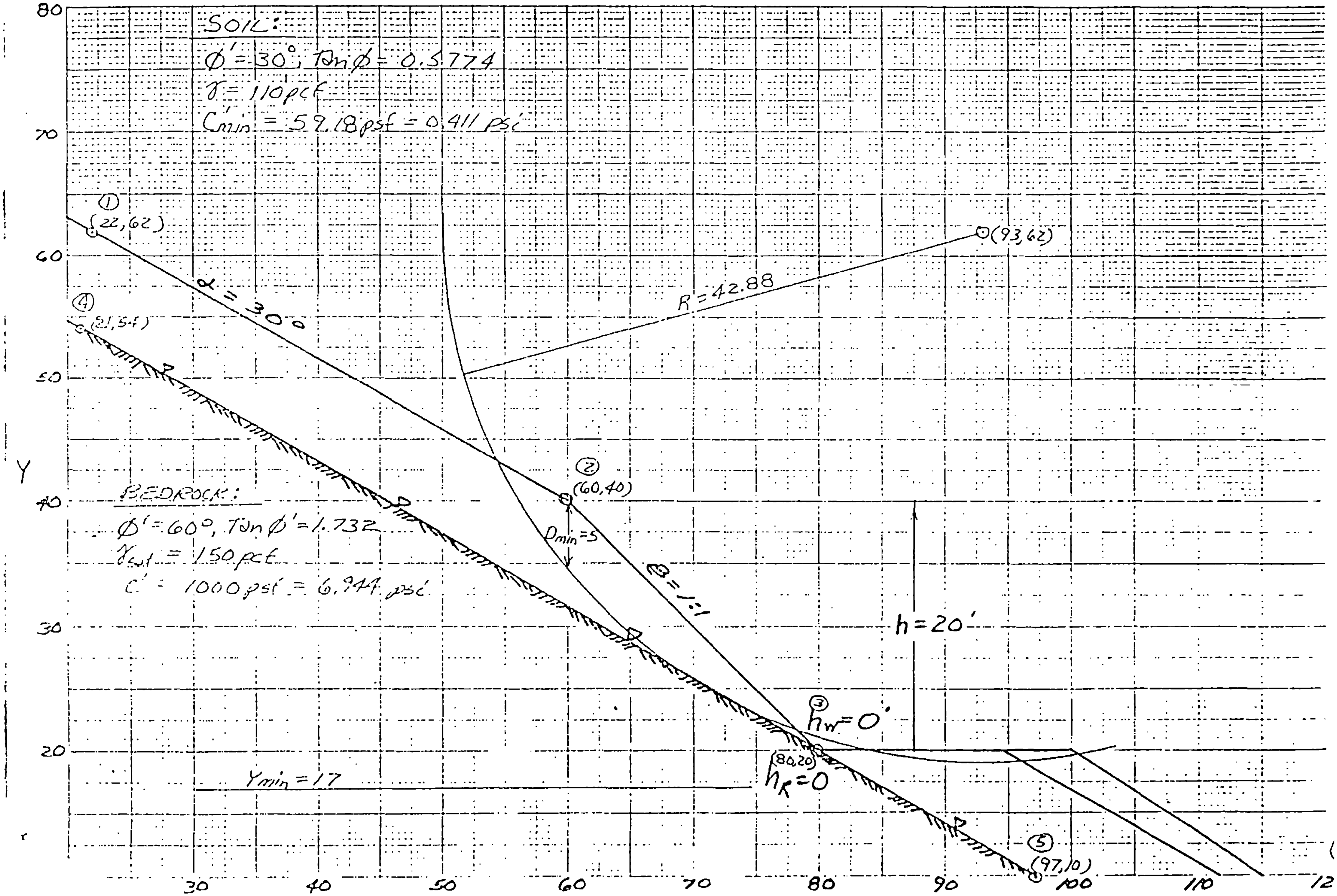
(11)



BEE 20x20 TO INCH

(12)

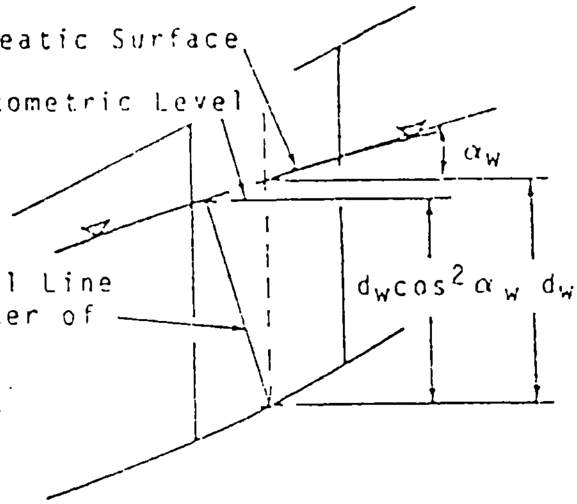
CROSS SECTION No. 12



CORRECTIONS TO "STABL 3":

① NO PHREATIC SURFACE SLOPE CORRECTION IN PORE PRESSURE ANALYSIS. (Neither Does "GEOSLIP")

Uses d_w Rather than $d_w \cos^2 \alpha_w$ - Results in Conservative Answer (the steeper α_w, the More Conservative).



from: "SSMOS"

Figure 3.--Definition of terms used in pore pressure analysis.

② NO "fo" CORRECTION FACTOR IN JANBU ANALYSIS:

Simplified Janbu Method of Slices. For each assumed FS:

Calculated JMS FS =

$$\frac{f_o \Sigma \left[(cb + (W - Ub)\tan \phi)(1 + \tan^2 \theta) \div (1 + \frac{\tan \theta \tan \phi}{\text{assumed FS}}) \right]}{\Sigma W \tan \theta + 1/2\, \partial_w z_w^2}$$

where

$$f_o = 1 + k\,[d/\ell - 1.4\,(d/\ell)^2]\ \text{(figure 2)};$$

$k = 0.31$ for $c = 0$;
$k = 0.50$ for $c > 0$ & $\phi > 0$.

from: "SSMOS"

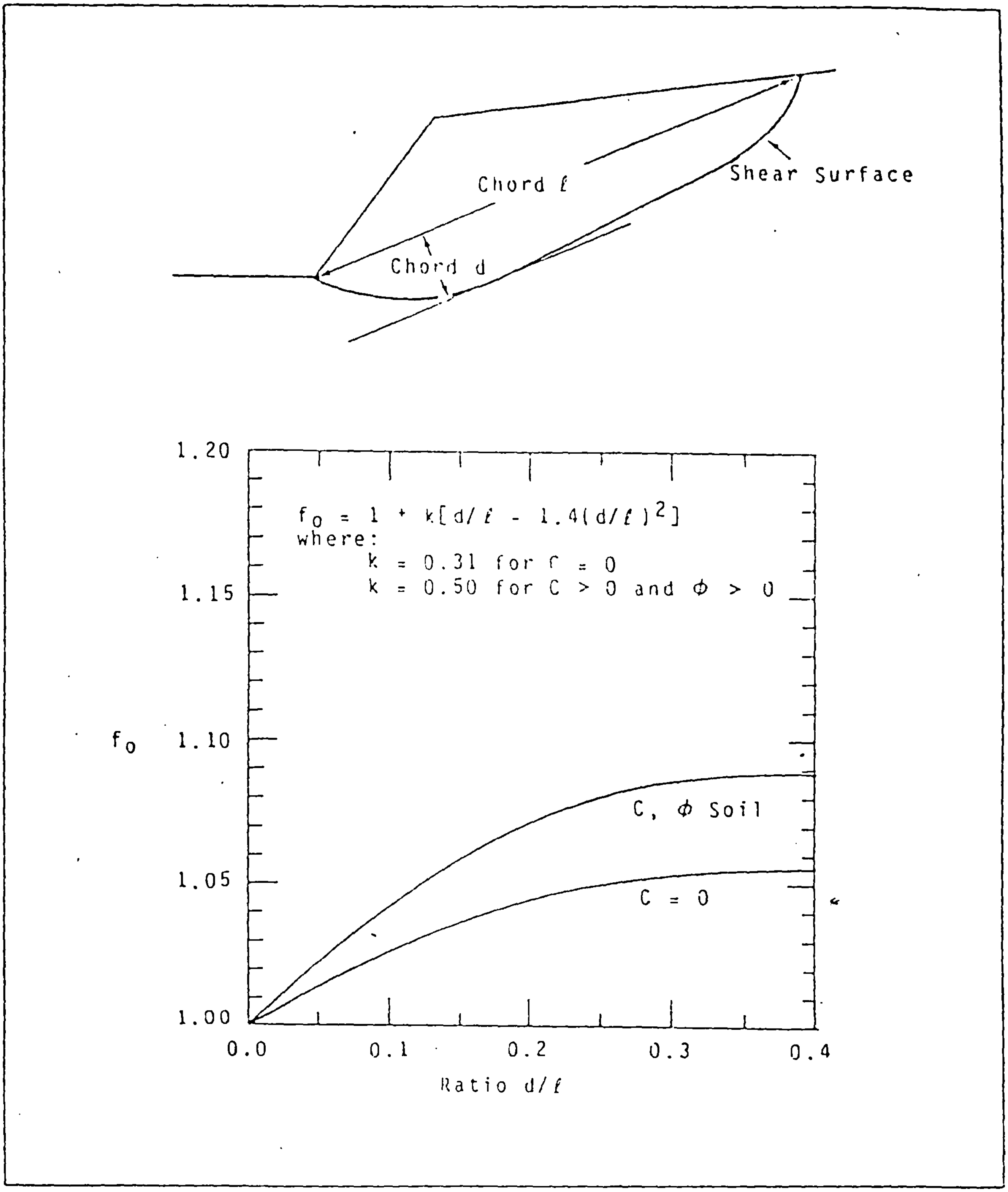


Figure 2.--Correction factor f_o as function of curvature ratio d/ℓ and type of soil.

From: "SSMOS"

Since fo is always Greater than 1.0, by Eliminating, Answer is Even More Conservative.

③ TERRY HOWARD, U. of IDAHO, ALSO FOUND ERROR IN EARTHQUAKE LOADING ANALYSIS AND CORRECTED (I Don't Have the Details on this One but Will Get Them and Document).

④ RANDOM SEARCH FOR MINIMUM F.S. IS CUMBERSOME FOR CIRCULAR ARC FAILURES WITH SLOPING BEDROCK & PHREATIC SURFACES (Radius & X, Y Incremental or Grid such as "DTIS & BISHOP" Has is Much Easier To Control.)

⑤

(?)

Terry to add & discuss

MODIFICATIONS TO PROGRAM

STABL3

- PERSONAL COMPUTER VERSION -

ENCORPORATING

- THIN SLICES
- PORE PRESSURE CORRECTION
- JANBU CORRECTION FACTOR

DAVID HALL
TERRY HOWARD

DEPARTMENT OF GEOLOGICAL ENGINEERING
UNIVERSITY OF IDAHO

AUGUST 1986

CONTENTS

LEVEL 3 MODIFICATIONS

I IMPLEMENTATIONAL

A. ADDED GRAPHICS SUBROUTINES TO EMULATE CALCOMP ROUTINES: PLOT, PLOTS, NUMBER, SYMBOL, AXIS with sub-functions STSYM, SPSYM, SAXIS.

We added a number of routines to emulate the CALCOMP routines PLOT, PLOTS, NUMBER, SYMBOL (both "special" and "standard"), and AXIS as called by STABL3. They are not all full implementations of the corresponding CALCOMP routines.

1) DATA TO FILE FOR SUBSEQUENT PLOT ON PLOTTER OR SCREEN

These routines write to a disk file the required data for each routine, for subsequent use by a graphics program. We have developed two programs to read the plot file and plot to either the PC screen or a Houston Instruments DM/PL pen plotter. We have also developed a method to import the data for use by the GOLDEN software series for nice plots on dot matrix printers.

2) DESCRIPTION OF GRAPHICS SYSTEM

+) FILE FORMAT

The plot file is a sequential ASCII file with values within records separated by commas. The file is composed of a number of "entries", one for each call to PLOT, AXIS, SYMBOL, or NUMBER. Each entry consists of a record with an entry code followed by an X and a Y value. Some of the entries will have a second record with data specific to that plot command.

The supported CALCOMP routines, and their respective entry codes used in the plot file, are defined below. The actual format and description of parameters stored are given under the individual subroutine descriptions.

PLOTS	--	Opens plot file. No data generated.
PLOT	--	Code 1 (for IPEN = +/- 2)
		Code 2 (for IPEN = +/- 3)
NUMBER	--	Code 3. Two records.
SYMBOL	--	Code 4 (special symbol). Two records.
		Code 5 (standard symbol). Two records.
AXIS	--	Code 6. Two records.

+) PLOTDMP

Program written in BASIC to read the plot file and generate the specified plot on a pen plotter supporting the Houston Instruments DM/PL command set.

+) PEAGLE

Program written in BASIC to read the plot file and generate the specified plot on a PC graphics screen.

+) GOLDEN SOFTWARE LINK

The plot file can also be rearranged slightly to match the formatting requirements for input files to the GOLDEN software products, which create nice plots on a dot matrix printer (such as the Epson).

3) SUBROUTINE DESCRIPTIONS

Each CALCOMP emulation routine is briefly described here, including a description of the data format used in the plot file.

+) PLOTS(IBUF,NLOC,LDEV)
Opens plot file to receive commands from subsequent calls to CALCOMP emulation routines. The user is asked for a file name to be used (default TEMPPLOT); maximum length of file name is 21 characters. File must not already exist. The file is opened as unit 13. IBUF, NLOC, and LDEV are not used, and are ignored. No output to the file is generated.

+) PLOT(XPAGE,YPAGE,IPEN)
If IPEN = 999 then the plot file is closed, and a message to that effect is printed on the screen.
If IPEN = 2 or -2, write to file

```
   1, XPAGE, YPAGE                     [I2 , F10.2 , F10.2]
```

If IPEN = 3 or -3, write to file

```
   2, XPAGE, YPAGE                     [I2 , F10.2 , F10.2]
```

Note that negative values of IPEN are not currently differentiated from their positive counterparts.

+) NUMBER(XPAGE,YPAGE,HT,FPN,ANGLE,NDEC)
Write to file:

```
   3, XPAGE, YPAGE                     [I2 , F10.2 , F10.2]
   HT, FPN, ANGLE, NDEC          [F8.2 , F12.6 , F8.3 , I3]
```

+) SYMBOL(X,Y,HT,IBCD,ANGLE,NCH)
SYMBOL(X,Y,INTEQ,ANGLE,ICODE)

Special or standard symbol plot. Standard symbol (NCH/ICODE less than zero) has maximum text length of 50 characters, and is assumed to be passed in A4 chunks. Write to file:

```
   4, X, Y                            [I2 , F10.2 , F10.2]
   HT, INTEQ, ANGLE, ICODE        [F8.2 , I3 , F8.3 , I3]
   5, X, Y                            [I2 , F10.2 , F10.2]
   HT, ANGLE, NCH, STRING   [F8.2 , F8.3 , I3 , "---------"]
```

4) AXIS(XPAGE,YPAGE,TITLE,NCH,AXLEN,ANGLE,FIRSTV,DELTAV,
R1,I1,I2,I3,R2)

Generate an axis, with a title (maximum 50 characters, in A4 variables). CALCOMP specifies that the sign of NCH specifies which side of the axis line the title is to appear. We honor this for the call to AXIS, but within the plot file, we make NCH positive, and use the sign of AXLEN to specify this. Also, some versions of the CALCOMP manuals say nothing about the last 5 arguments, but STABL3 uses them, so we pass them on and store them in the plot file. Writes to file:

```
   6, XPAGE, YPAGE                       [I2 , F10.2 , F10.2]
   NCH, AXLE, ANGLE, FIRSTV, DELTAV, R1,I1,I2,I3,R2, TITLE

     [I4,F8.3,F8.3,F8.3,F8.3,F8.3,I3,I3,I3,F8.3,"---------"]
```

B. SOURCE (& OBJECT) CODE BROKEN INTO 14 MANAGEABLE CHUNKS:

```
STABL3   - READER   - QUIT
PROFIL   - (SOIL)
ANISO
WATER    - LOADS    - EQUAKE
LIMITS   - INTSCT   - (INTSC2)
SURFAC   - RANDOM   - (BLOCK)
RANSUF
BLKSUF
SLICES   - SORT     - EXECUT    - BLOCK2
WEIGHT   - SOILWT
FACTR    - [CFJ]
SCALER   - PLOTIN   - (PLOTN2)  - (PLOTN3)
PLTN     - (PLT2)   - (PLT3)    - (PLT4)
         - POSTN    - [URAN]
PLOTTING SUBROUTINES
```

C. ENTRY

1) The mainframe version had ENTRIES into several of the subroutines. Microsoft FORTRAN does not seem to support them, so we changed the program slightly to get around this limitation. The ENTRY points are:

ENTRY POINT(S)	in	SUBROUTINE
SOIL		PROFIL
INTSC2		INTSCT
BLOCK		RANDOM
PLOTN2, PLOTN3, PLOTN4		PLOTIN
PLT2, PLT3, PLT4		PLTN

Subroutines PROFIL, RANDOM, PLOTIN, and PLTN originally had no arguments. We added one argument each, IENTRY, to indicate whether to execute the main routine or to jump to an alternative entry point, as follows:

```
+) PROFIL(IENTRY)
           1  PROFIL
           2  SOIL
   RANDOM(IENTRY)
           1  RANDOM
           2  BLOCK
   PLOTIN(IENTRY)
           1  PLOTIN
           2  PLOTN2
           3  PLOTN3
   PLTN  (IENTRY)
           1  PLTN
           2  PLT2
           3  PLT3
           4  PLT4
```

2) INTSCT already has a long argument list, including a value returned as INTS (the last argument in the list). We chose to set this variable to 1 to specify a call to INTSCT, or a 2 to specify a call to ENTRY INTSC2:

```
INTSCT(....,INTS)
        1  INTSCT
        2  INTSC2
```

D. URAN random number generator

1) describe
2) listing
3) test overview

E. ERROR CODES, ETC.
The mainframe version used

```
DATA KEYW/6HPROFIL,5HLOADS,5HWATER.../,
```

which gave error messages from the Microsoft compiler when we tried to compile it. These were all converted to

```
KEYW(1)="PROFIL"
KEYW(2)="LOADS"
KEYW(3)="WATER"
etc.
```

F. Array WAR(100) was passed to routine PLOTS. Neither our mainframe nor our PC version support this, and it was deleted.

G. FILE SYSTEM FOR PC

1) FILEIN	: INPUT DATA FILE	UNIT 5	[Opened in MAIN]
2) FILEUT	: OUTPUT FILE	UNIT 6	[Opened in MAIN]
3) FILEN	: PLOT FILE	UNIT 13	[Opened in PLOTS]

H. COMPILER DIRECTIVE $DO66 USED
Use FORTRAN IV convention for do loops (i.e., run through the loop at least once)

II ALGORITHMIC MODIFICATIONS TO PROGRAM STABL3

Three algorithmic changes have been made to STABL3. They are:

- Very thin slices correction (subroutine WEIGHT),
- Pore pressure correction (subroutine WEIGHT), and
- Janbu correction factor, Fo (subroutine FACTR).

Each of these modifications is described in detail below. Listings of the modified subroutines WEIGHT and FACTOR (and the added function CFJ) are given in the appendix.

A. MODIFICATION FOR VERY THIN SLICES

STABL3 divides the soil mass into vertical slices at each horizontal coordinate defining

- trial failure surface
- piezometric surfaces
- soil type boundaries
- ground surface

and sometimes the resulting slices end up being very thin; too thin to be meaningful for analysis, and thinner than the computer's numerical accuracy can handle. This condition results in an error message being generated from within subroutine WEIGHT:

```
***********************************************
******  INPUT ERROR - TRIAL FAILURE SURFACE  ******
******              EXTENDS ABOVE THE        ******
******              GROUND SURFACE           ******
***********************************************
```

We skip potential slices which are so thin that the top of the slice, YT, is not found to be higher than the bottom of the slice, YB. One statement, marked DH010585, is modified in subroutine WEIGHT, and it fits in as follows.

```
=====================================================

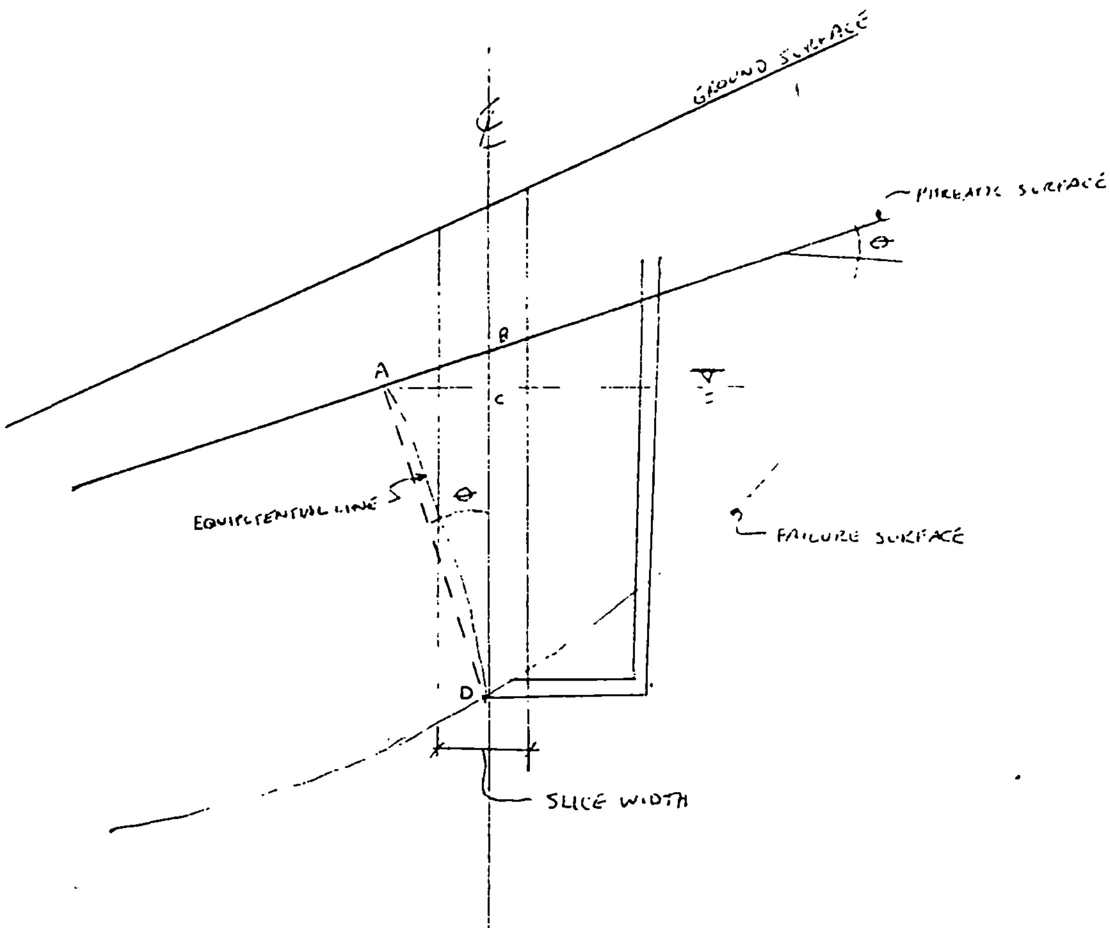
    --
    --
C
C   -------------------------------------------
C   DETERMINE BASE OF SLICE AND ITS INCLINATION
C   -------------------------------------------
C
      DO 4 J=JB,NSURF
          --
          --
*         IF (INTS.EQ.1 .AND.YT.GT.YB ) GOTO 6
                        ==============                THIS PART ADDED.
  4   CONTINUE
  6   ...

=====================================================
```

Note another potential problem: for the DO 3, DO 4, and DO 7 loops, you jump out of the loop if an intersection is found (if INTS=1), or drop out of the loop if no intersection is found. There is no check to ensure that a valid intersection was found.

B. PORE PRESSURE CORRECTION, Kw

For steady-state flow, the piezometric surface for any point will rise to the level where the equipotential passing this point intersects the phreatic surface.



If the phreatic surface slopes, an error $\overline{BC}$ is introduced; that is, the program uses $\overline{BD}$ when it should use $\overline{CD}$.

If θ is the angle of the phreatic surface, then the error $\overline{BC}$ is

$$\overline{BC} = \overline{AB} \sin \theta$$
$$\overline{BC} = (\overline{BD} \sin \theta) \sin \theta$$
$$\overline{BC} = \overline{BD} \sin^2 \theta$$

and the correct pore pressure is

$$u = \overline{BD} (1-\sin^2 \theta)$$

In the unmodified STABL3, we have for each slice "I":

```
IF (YW(K) > YB)        [THAT IS, IF THE PHREATIC SURFACE IN QUESTION
                        IS WITHIN THE SOIL SLICE]
     THEN

          UALPHA(I) = (YW(K)-YB) * 62.4 * DX(I) / COS (ALPHA)
```

$$\text{or}\quad UALPHA = \frac{BD \cdot 62.4 \cdot DX}{COS\ (ALPHA)}$$

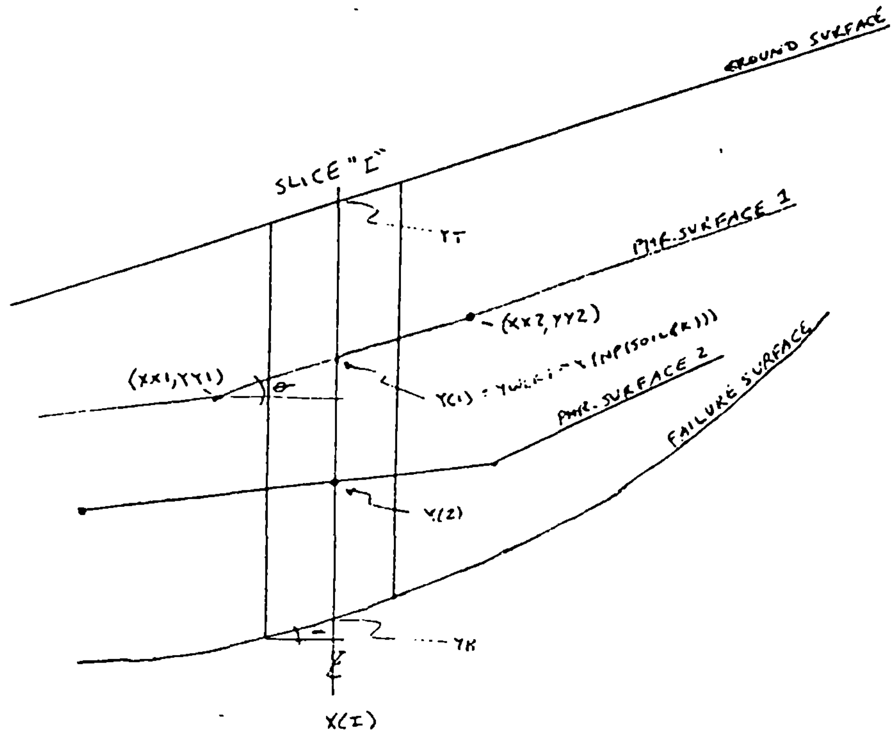
which is incorrect for a sloping phreatic surface. The formula for UALPHA was modified as follows:

$$UALPHA = \frac{BD\ (1-SIN^2\ \theta)\ \cdot 62.4 \cdot DX}{COS\ (ALPHA)}$$

Using the notation in the following figure (and that used in the program), we have:

```
IN2 = NP(SOIL(K))
IN1 = JW(IN2)
XX1 = XPIEZ(IN2,IN1-1)
XX2 = XPIEZ(IN2,IN1)
YY1 = YPIEZ(IN2,IN1-1)
YY2 = YPIEZ(IN2,IN1)
THETA = ATAN((YY2-YY1)/(XX2-XX1))
STHETA = SIN(THETA)
THETAC = (1-SIN2 (THETA))
UALPHA(I) = THETAC * (YW(K)-YB) * UWAT * DX(I) / CA
```

ALPHA	ANGLE OF BASE OF THE SLICE
CA	COSINE OF ANGLE ALPHA
DX	WIDTH OF THE SLICE
JW	ARRAY CONTAINING SUBSCRIPT OF LAST POINT DEFINING EACH PIEZOMETRIC SURFACE, USED TO DETERMINE THE INTERSECTION OF THE CENTERLINE OF A SLICE WITH THE PIEZOMETRIC SURFACE.
NP	ARRAY CONTAINING NUMBER OF PIEZOMETRIC SURFACE FOR EACH SOIL TYPE.
SOIL	ARRAY CONTAINING INDICES OF THE SOIL TYPE OF EACH SUBSECTION WITHIN A SLICE.
STHETA	SINE OF THE ANGLE THETA
THETA	ANGLE OF PHREATIC SURFACE
THETAC	CORRECTION FACTOR TO BE USED: $1-SIN^2(THETA)$
UALPHA	HYDROSTATIC FORCE ACTING AT THE BASE OF THE SLICE
UWAT	UNIT WEIGHT OF WATER
XPIEZ	ARRAY CONTAINING X COORDINATES OF POINTS DEFINING WATER SURFACE.
YPIEZ	ARRAY CONTAINING Y COORDINATES OF POINTS DEFINING WATER SURFACE.
YW	ARRAY CONTAINING Y COORDINATE OF THE PIEZOMETRIC SURFACE FOR EACH SOIL TYPE OF A SLICE; YW is a reordering of Y such that YW(K) = Y(NP(SOIL(K))).



The modifications can be found in subroutine WEIGHT, marked with DH090485, and fit into the scheme of the subroutine as follows:

```
=====================================================

      DO 2 I=1,NSLICE                          (FOR EACH SLICE)
      -
      -
C
C     DETERMINE POSITION OF WATER TABLE FOR ALL SOILS IF PRESENT
C
         DO 25 N=1,NPZ                         (FOR EACH PHR. SURFACE)
            -
            -
 25      -
                     --------------------------
                      PORE PRESSURE CORRECTIONS
                     --------------------------
  2 -

=====================================================
```

** NOTE -- if there is more than one phreatic surface, then the results are not guaranteed. Only the "last" phreatic surface is used in the correction. Further work is necessary to separate, within the program, the difference between phreatic surfaces and piezometric surfaces.

C. JANBU CORRECTION FACTOR, Fo

We need FS = Fo * F

where F is the factor of safety calculated without the correction factor, and FS is the corrected factor of safety.

We have added a function CFJ (Correction Factor Janbu) which returns to subroutine FACTR the required correction factor Fo for the trial failure surface. Fo is defined as

$$Fo = 1 + k * [(D/L) - 1.4 * (D/L)^2]$$

where

k = 0.31 for cohesionless soils
  = 0.50 otherwise.

This presents a problem, since we may have some of each type of soil in a particular problem. For the first cut, we simply use k=0.31 if the majority of slices are of cohesionless soil; otherwise we use k=0.50. To do this, we count the number of slices for which C=0, and pass this (NCO) and the total number of slices (NSLICE) to CFJ. The geometry of the trial failure surface is also passed to CFJ, in common BLK05.

The factor of safety for the trial failure surface is calculated in FACTR by an iterative process, until

1. FS converges (successive iterations differ by less than 0.005), or
2. 10 iterations without sufficient convergence.

We calculate Fo for each iteration, and apply the correction factor as we go. However, Fo does not change between iterations, and so should not affect convergence for the factor of safety figure*. It would be more efficient to either

1. calculate the correction factor once before we start the convergence iterations, and apply the factor each time, or
2. converge upon a non-corrected factor of safety figure, and then calculate and apply the correction factor Fo.

The Janbu modifications are in subroutine FACTR, marked 051486DH, and in added function CFJ. These are listed in the appendix.

----

* The convergence tolerence will effectively be changed, but only very slightly, since Fo can be expected to be about 1.02 to 1.06.

MODIFICATION SCHEME FOR JANBU CORRECTION -- SUBROUTINE FACTR

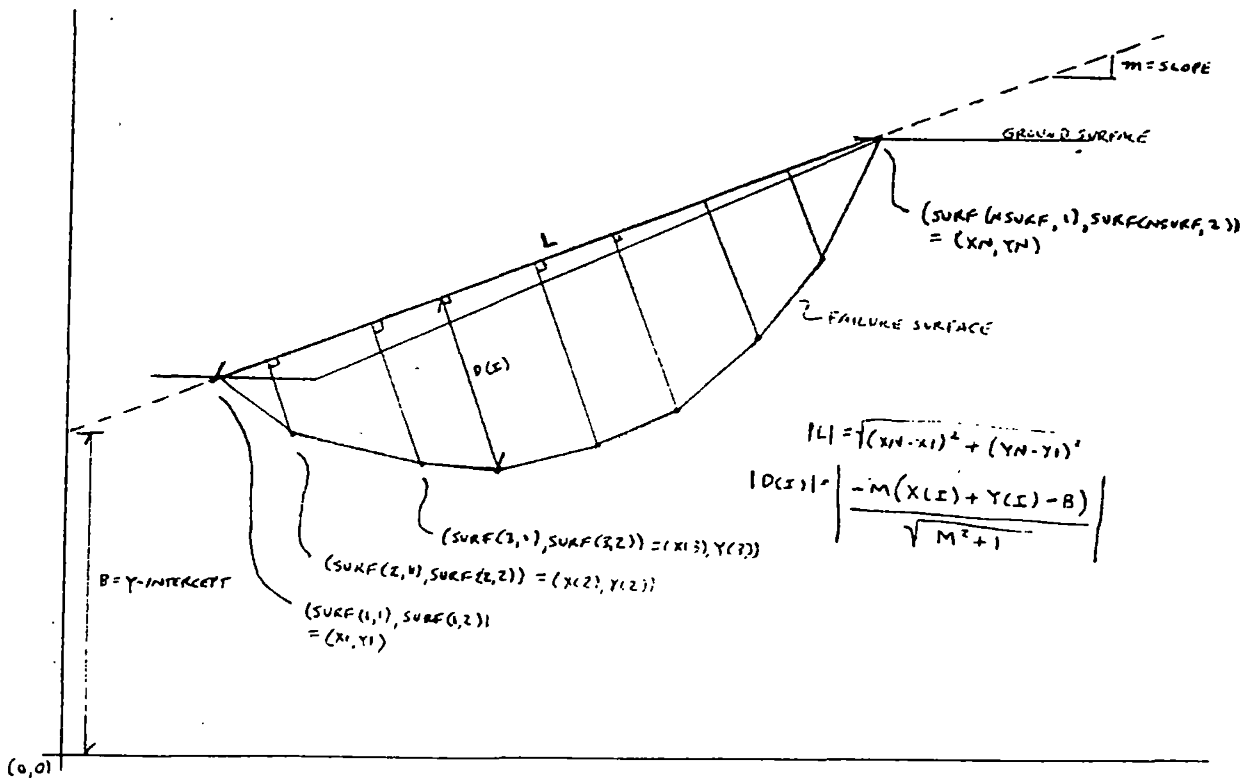
```
      -
      -
      SUMB=0.0
*     NCO=0
*C  NCO IS NUMBER OF SLICES WITH COHESIONLESS SOIL
 C
 C  ---------------------------------
 C  CALCULATE REQUIRED ANGLE FUNCTIONS
 C  ---------------------------------
 C
      DO 2 I=1,NSLICE
         -
         -
         IF (MB.EQ.1) GOTO 40                    (IF BISHOP)
*C
*C  COUNT NUMBER OF SLICES FOR WHICH C=0
*C
*        IF (CSLICE.LE.0.01) NCO=NCO+1           (OR VERY CLOSE TO 0)
 C
 C  SIMPLIFIED JANBU A-TERMS
 C
         -
         -
  2   CONTINUE
      -
      -
      DO 10 J=1,10                               (SAFETY FACTOR ITERATION)
*C
*C  ------------------------------------------------
*C  CALCULATE CORRECTION FACTOR FOR JANBU CALCULATION
*C  ------------------------------------------------
*C
*        F0=1.0                                  (ASSUME Fo IS 1.0 IN CASE
                                                 BISHOP'S IS BEING USED)
*        IF (MB.NE.1) F0=CFJ(NC0,NSLICE)         (IF JANBU, CALCULATE
                                                 CORRECTION FACTOR Fo)
*C
*        FNEW = F0 * SUMT/SUMB                   (WAS: FNEW=SUMT/SUMB)
 C
 C  ---------------------
 C  CHECK FOR CONVERGENCE
 C  ---------------------
 C
         IF (ABS(FNEW-FOLD).LT..005) GOTO 15     (IF FS CONVERGES WITHIN 10
                                                 ITERATIONS, RETURN)
 10   FOLD=FNEW
      -
      -
 15   FS=FNEW                                    (PERHAPS SHOULD CALL CFJ
                                                 HERE:
      -                                          15 F0=1.0
      -                                             IF (MB.NE.1)F0=CFJ()
                                                    FS = F0 * FNEW
```

FUNCTION CFJ returns the Janbu correction factor for the trial failure surface given the failure surface geometry (in COMMON BLK05); and the number of slices representing cohesionless soils and the total number of slices (passed as arguments).

CFJ calculates and returns $Fo = 1 + K * [(D/L) - 1.4 * (D/L)^2]$

where K, D, and L are defined as follows:

- K = 0.31 for cohesionless soils (C=0)
  = 0.50 otherwise (C > 0 and PHI > 0)
  Since different slices can have different values for soil cohesion, we had to decide upon an appropriate value for K for the overall problem. For this version, we use either 0.31 or 0.50 depending upon the ratio of cohesionless slices to the total number of slices. If this ratio is greater or equal to 1/2, then we use K=0.31. An alternative approach would be to use a sliding K value depending upon the relative size of the ratio NCO/NSLICE.
- L = length of cord L in the following figure
- D = length of longest cord D in the following figure
  (the D's are cords between trial failure surface coordinates and cord L such that they intersect L at a right angle)



A P P E N D I X

MODIFIED SUBROUTINE LISTINGS

```
$D066
      SUBROUTINE WEIGHT
C     ---------------------------------------------------------------------STA53920
C     -----------------------------------------------------------------
C                                SUBROUTINE WEIGHT
C     -----------------------------------------------------------------
C     -----------------------------------------------------------------
C
C     FUNCTIONS -
C
C          DETERMINES THE INCLINATION OF THE TOP AND BOTTOM OF EACH
C          SLICE.
C
C          DETERMINES THE RESULTANT WATER FORCES AT THE TOP AND BASE OF
C          EACH SLICE IF PRESENT.
C
C          DETERMINES THE TOTAL WEIGHT OF EACH SLICE AND THE SOIL TYPE AT
C          THE BASE OF EACH SLICE.
C
C          DETERMINES THE SURCHARGE FORCE, IF ANY, AT THE TOP OF EACH
C          SLICE.
C
C     MODIFIED JAN 15, 1985     DAVID HALL                                  DH011585
C          FIX FOR SLICES OF MICROSCOPIC WIDTH                              DH011585
C
C     MODIFIED SEP 04, 1985     DAVID HALL & PAUL SWETIK                    DH090485
C          PORE PRESSURE CORRECTION                                         DH090485
C
C     -----------------------------------------------------------------
C     -----------------------------------------------------------------
C
      COMMON /BLK01/IANGL,IBLK,IEXIT,ICIRC,ILIMIT,IPLOT,IREAD,ISEARC,
     1         IBLK2,ISOIL,ISTR,ISURC,ISURF,IWAT,RD,TOL
      COMMON /BLK02/BNDS(100,4),C(20),GAMMA(20),GSAT(20),ITP(100),NBND,
     1              NSOIL,NTOP,PHI(20),RU(20),CU(20),NP(20)
      COMMON /BLK03/UWAT,NPZ,NPIEZ(10),XPIEZ(10,40),YPIEZ(10,40)
      COMMON /BLK04/DELTA(10),LOAD(10),NSURC,SURC(10,2),YSURC(10,2)
      COMMON /BLK05/NSURF,SURF(100,2)
      COMMON /BLK08/NSLICE,X(300)
      COMMON /BLK09/ALPHA(200),BETA(200),DX(200),SLTP(200),UALPHA(200),
     1              UBETA(200),WTT(200)
      COMMON /BLK10/DELT(200),P(200)
      COMMON /BLK11/CAVT,KCOEF,VKCOEF
      COMMON /BLK15/M,MB
      COMMON /BLK21/HIGHT(200),HGHTEQ(200)
      DIMENSION YI(20),YW(20),JW(10),Y(10)
      REAL KCOEF,LOAD
      INTEGER SOIL(20),SOILTP,SLTP
      JT=1
      JB=2
      JS=1
      IF (NPZ.EQ.0) GO TO 110
      DO 13 J=1,NPZ
```

```
      JW(J)=2
   13 CONTINUE
 110  CONTINUE
      NTOP1=NTOP+1
C
C   ---------------------------------------                             STA56470
C   CALCULATE THICKNESS AND MIDPOINT OF SLICE
C   ---------------------------------------
C
      DO 2 I=1,NSLICE
C
C     INITIALIZE THE SLICE HEIGHT AND THE HEIGHT OF THE CENTROID OF     DH072886
C     THE EARTHQUAKE FORCE ABOVE THE BASE OF THE SLICE
C
      HIGHT(I) = 0.0
      HGHTEQ(I) = 0.0
      DX(I)=X(I+1)-X(I)
      X(I)=(X(I)+X(I+1))/2.
      DO 16 J=1,NSOIL
      YW(J)=0.
   16 CONTINUE
C
C   ----------------------------------------                            STA56640
C   DETERMINE TOP OF SLICE AND ITS INCLINATION
C   ----------------------------------------
C
      DO 3 J=JT,NTOP
      JTN=J
      INTS=2
      CALL INTSCT(BNDS(J,1),BNDS(J,2),BNDS(J,3),BNDS(J,4),0.,0.,0.,0.,
     1   X(I),YT,INTS)
      IF(INTS.EQ.1)GO TO 5
    3 CONTINUE
    5 JT=JTN
      J=JTN
      BETA(I)=ATAN((BNDS(J,2)-BNDS(J,4))/(BNDS(J,1)-BNDS(J,3)))
C
C   -----------------------------------------
C   DETERMINE BASE OF SLICE AND ITS INCLINATION
C   -----------------------------------------
C
      DO 4 J=JB,NSURF
      JTN=J
      INTS=2
      CALL INTSCT(SURF(J-1,1),SURF(J-1,2),SURF(J,1),SURF(J,2),0.,0.,0.,
     1   0.,X(I),YB,INTS)
C
      IF(INTS.EQ.1.AND.YT.GT.YB)GO TO 6                                 DH011585
    4 CONTINUE
    6 JB=JTN
      J=JTN
      ALPHA(I)=ATAN((SURF(J-1,2)-SURF(J,2))/(SURF(J-1,1)-SURF(J,1)))
      CA=COS(ALPHA(I))
```

```
C
C   ------------------------------------------------
C   CHECK IF TRIAL SURFACE IS BELOW THE GROUND SURFACE
C   ------------------------------------------------
C
      IF(YT.GT.YB)GO TO 18
      WRITE(6,101)
  101 FORMAT(//,
     110X'************************************************'/              STA57000
     110X'******  INPUT ERROR - TRIAL FAILURE SURFACE  ******'/
     110X'******                EXTENDS ABOVE THE      ******'/
     110X'******                GROUND SURFACE         ******'/
     110X'************************************************'/)
      KEY= 72
      WRITE(6,72)KEY,I,X(I),YT,YB,DX(I)
   72 FORMAT(/,'  XXX KEY=',I4,'  XXX ',I10,5F15.5)
      IF(ISEARC.EQ.0)GO TO 22
      WRITE(6,104)NSURF
  104 FORMAT(///,
     110X,'THE TRIAL FAILURE SURFACE IN QUESTION IS DEFINED',/,
     110X,'BY THE FOLLOWING',I3,
     1    ' COORDINATE POINTS',///,
     1    12X,'POINT',6X,'X-SURF',6X,'Y-SURF',/
     1    13X,'NO.',8X,'(FT)',8X,'(FT)',/)
      WRITE(6,105)(J,SURF(J,1),SURF(J,2),J=1,NSURF)
  105 FORMAT(12X,I3,2X,2F12.2)
   22 CALL PLTN(4)
      CALL QUIT
   18 K=1
      SOIL(1)=ITP(JT)
      IF(NTOP.EQ.NBND)GO TO 12
C
C   ------------------------------------------------
C   DETERMINE POSITIONS OF SOIL TYPE INTERFACES, IF ANY
C   AND DETERMINE SOIL TYPE AT BASE OF SLICE.
C   ------------------------------------------------
C
      DO 9 J=NTOP1,NBND
      INTS=2
      CALL INTSCT(BNDS(J,1),BNDS(J,2),BNDS(J,3),BNDS(J,4),0.,0.,0.,0.,
     1   X(I),YI(K),INTS)
      IF(INTS.NE.1)GO TO 9
      IF(YI(K).LE.YB)GO TO 12
      K=K+1
      SOIL(K)=ITP(J)
    9 CONTINUE
   12 SLTP(I)=SOIL(K)
      SOILTP=SLTP(I)
      UALPHA(I)=0.
      UBETA(I)=0.
      IF(IWAT.EQ.0)GO TO 10
C
C   ------------------------------------------------------------      STA57430
```

```
C     DETERMINE POSITION OF WATER TABLE FOR ALL SOILS IF PRESENT
C     ------------------------------------------------------------
C
      DO 25 N=1,NPZ
      JJ=JW(N)
      NN=NPIEZ(N)
      DO 7 J=JJ,NN
      JTN=J
      INTS=2
      CALL INTSCT(XPIEZ(N,J-1),YPIEZ(N,J-1),XPIEZ(N,J),YPIEZ(N,J),
     1   0.,0.,0.,0.,X(I),Y(N),INTS)
      IF(INTS.EQ.1)GO TO 8
    7 CONTINUE
    8 JW(N)=JTN
   25 CONTINUE
      DO 26 J=1,K
      YW(J)=Y(NP(SOIL(J)))
   26 CONTINUE
C                                                                       DH090485
      IN2=NP(SOIL(K))                                                   DH090485
      IN1=JW(IN2)                                                       DH090485
      THETA=ATAN((YPIEZ(IN2,IN1)-YPIEZ(IN2,IN1-1))/(XPIEZ(IN2,IN1)-     DH090485
     $  XPIEZ(IN2,IN1-1)))                                              DH090485
      STHETA=SIN(THETA)                                                 DH090485
      THETAC=1-STHETA*STHETA                                            DH090485
C                                                                       DH090485
      IF(YW(K).GT.YB)UALPHA(I)=THETAC*(YW(K)-YB)*UWAT*DX(I)/CA          DH090485
      IF(YW(1).LT.YT)GO TO 10
C
C     ------------------------------------------------------------      STA57640
C     CALCULATE RESULTANT WATER FORCE AT TOP OF SLICE, IF PRESENT
C     ------------------------------------------------------------
C
      UBETA(I)=DX(I)*(YW(1)-YT)*UWAT/COS(BETA(I))
C
C     ------------------------------------------------------
C     CALCULATE SLICE WEIGHT
C     ------------------------------------------------------
C
10    IF (MB.EQ.1) WTHEQ = 0.0
      IF(K.EQ.1)GO TO 14
      CALL SOILWT(YT,YI(1),ITP(JT),YW(1),WTT(I),I)
      IF (MB.EQ.1) WTHEQ = WTHEQ + ((YT + YI(1))/2.0 - YB)*WTT(I)
      GO TO 15
   14 CALL SOILWT(YT,YB,ITP(JT),YW(1),WTT(I),I)
      IF (MB.EQ.1) WTHEQ = WTHEQ + (YT-YB)/2.0*WTT(I)
      GO TO 21
   15 IF(K.EQ.2)GO TO 17
      K1=K-1
      DO 11 J=2,K1
      CALL SOILWT(YI(J-1),YI(J),SOIL(J),YW(J),WT,I)
      IF (MB.EQ.1) WTHEQ = WTHEQ + ((YI(J-1) + YI(J))/2.0 - YB)*WT
      WTT(I)=WTT(I)+WT
```

```
   11 CONTINUE
   17 CALL SOILWT(YI(K-1),YB,SOIL(K),YW(K),WT,I)
      IF (MB.EQ.1) WTHEQ = WTHEQ + (YI(K-1) - YB)/2.0*WT
      WTT(I)=WTT(I)+WT
   21 IF(YW(K).LT.YB.AND.RU(SOILTP).EQ.0..AND.CU(SOILTP).EQ.0.)GO TO 23
      IF(RU(SOILTP).EQ.0..AND.CU(SOILTP).EQ.0.)GO TO 24
      UALPHA(I)=UALPHA(I)+(WTT(I)*RU(SOILTP)+DX(I)*CU(SOILTP))/CA
   24 IF(KCOEF.EQ.0..AND.VKCOEF.EQ.0.)GO TO 23
      UALPHA(I)=UALPHA(I)-WTT(I)*(KCOEF*SIN(ALPHA(I))+VKCOEF*CA)
      IF(UALPHA(I).LT.CAVT)UALPHA(I)=CAVT
   23 P(I)=0.
      DELT(I)=0.
      IF(ISURC.EQ.0)GO TO 120
C
C    -------------------------------------
C    ASSIGN BOUNDARY LOAD TO SLICE, IF ANY
C    -------------------------------------
C
      DO 19 J=JS,NSURC
      JTN=J
      IF(X(I).LT.SURC(J,1))GO TO 20
      IF(X(I).GT.SURC(J,2))GO TO 19
      DELT(I)=DELTA(J)
      P(I)=LOAD(J)*DX(I)
      GO TO 20
   19 CONTINUE
   20 JS=JTN
  120 IF (MB.NE.1) GO TO 2
C
C     CALCULATE (1) THE SLICE HEIGHT AND (2) THE HEIGHT OF THE       DH072886
C     CENTROID OF THE HORIZONTAL EARTHQUAKE FORCE COMPONENT ABOVE THE
C     BASE OF THE SLICE
C
      HIGHT(I) = YT - YB
      HGHTEQ(I) = WTHEQ/WTT(I)
    2 CONTINUE
      RETURN
      END
```

```
$D066
      SUBROUTINE FACTR
C     ------------------------------------------------------------------
C     ------------------------------------------------------------------
C                              SUBROUTINE FACTR
C     ------------------------------------------------------------------
C   MODIFIED FOR JANBU CORRECTION FACTOR           5-14-86
C     ------------------------------------------------------------------
C
C    FUNCTIONS -
C
C         CALCULATES A-TERMS FOR FACTOR OF SAFETY CALCULATION.
C
C         CHECKS FOR CONDITION WHEN THE NORMAL FORCE AT THE BASE OF A
C         SLICE IS NEGATIVE.
C
C         CALCULATES FACTOR OF SAFETY WITH NEWTON-RALPHSON ITERATION.
C
C         IF NO CONVERGENCE BY TEN ITERATIONS, SURFACE COORDINATES
C         ARE PRINTED AND LACK OF CONVERGENCE INDICATED.
C
C         PRINTS FACTOR OF SAFETY IF ANALYSIS IS FOR SPECIFIED TRIAL
C         FAILURE SURFACE.
C
C    -------------------------------------------------------------------
C
C    -------------------------------------------------------------------
C
      COMMON /BLK01/IANGL,IBLK,IEXIT,ICIRC,ILIMIT,IPLOT,IREAD,ISEARC,
     1          IBLK2,ISOIL,ISTR,ISURC,ISURF,IWAT,RD,TOL
      COMMON /BLK02/BNDS(100,4),C(20),GAMMA(20),GSAT(20),ITP(100),NBND,
     1               NSOIL,NTOP,PHI(20),RU(20),CU(20),NP(20)
      COMMON /BLK05/NSURF,SURF(100,2)
      COMMON /BLK07/CSA(10,10),DIREC(10,10),ITPA(10),NDIREC(10),NSAL,
     1               PHIA(10,10)
      COMMON /BLK08/NSLICE,X(300)
      COMMON /BLK09/ALPHA(200),BETA(200),DX(200),SLTP(200),UALPHA(200),
     1               UBETA(200),WTT(200)
      COMMON /BLK10/DELT(200),P(200)
      COMMON /BLK11/CAVT,KCOEF,VKCOEF
      COMMON /BLK12/ANGS1,ANGS2,BPT,EPT,FRTYFV,FS,FSS(12),JJ,NSURFS(12),
     1               PERPEN,SURFS(100,2,12),TSURF,YBPT,YEPT,YMIN
      COMMON /BLK15/ M,MB
      COMMON /BLK20/RADIUS
      COMMON /BLK21/HIGHT(200),HGHTEQ(200)
      DIMENSION A1(200),A2(200),A3(200)
      EQUIVALENCE (ALPHA(1),A1(1)), (BETA(1),A2(1)), (DX(1),A3(1))
      INTEGER SLTP,SOILTP
      REAL KCOEF
      F1=0.
      SUMB = 0.0
      NCO=0                                                     051486DH
C     NCO IS NUMBER OF SLICES WITH ~~NON-~~C=0 SOIL             051486DH
```

```
C
C   ---------------------------------
C   CALCULATE REQUIRED ANGLE FUNCTIONS
C   ---------------------------------
C
      DO 2 I=1,NSLICE
      SD=SIN(DELT(I))
      CD=COS(DELT(I))
      SB=SIN(BETA(I))
      CB=COS(BETA(I))
      SA=SIN(ALPHA(I))
      CA=COS(ALPHA(I))
      TA=SA/CA
      SOILTP=SLTP(I)
      TP=TAN(PHI(SOILTP)*RD)
      CSLICE=C(SOILTP)
      IF(ISTR.EQ.0)GO TO 3
      DO 5 J=1,NSAL
      IF(SLTP(I).NE.ITPA(J))GO TO 5
      ND=NDIREC(J)
      IF(ALPHA(I).GE.DIREC(J,1))GO TO 8
      TP=TAN(PHIA(J,1)*RD)
      CSLICE=CSA(J,1)
      GO TO 3
    8 DO 4 K=2,ND
      IF((ALPHA(I).LT.DIREC(J,K-1)).OR.(ALPHA(I).GE.DIREC(J,K)))GO TO 4
      TP=TAN(PHIA(J,K)*RD)
      CSLICE=CSA(J,K)
      GO TO 3
    4 CONTINUE
    5 CONTINUE
C
C   ---------------------------------------------
C   CHECK IF THE DENOMINATOR OF THE EXPRESSION FOR
C   THE EFFECTIVE NORMAL FORCE IS ZERO OR NEGATIVE
C   ---------------------------------------------
C
    3 F=-TA*TP
      IF(F.GT.F1)F1=F
C
C   ------------------------------------------------------------
C   CALCULATE A-TERMS REQUIRED FOR FACTOR OF SAFETY CALCULATION
C   ------------------------------------------------------------
C
      IF (MB.EQ.1) GO TO 40
C                                                              051486DH
C    COUNT THE NUMBER OF SLICES FOR WHICH C=0                  051486DH
C                                                              051486DH
      IF(CSLICE.LE.0.01) NCO=NCO+1                             051486DH
C
C     SIMPLIFIED JANBU A-TERMS
C
      A0 = CSLICE*DX(I) + TP*(WTT(I)*(1.0-VKCOEF) - UALPHA(I)*CA
```

```
     1      + UBETA(I)*CB + P(I)*CD)
      A1(I) = A0/CA**2
      A2(I)=WTT(I)*(TA+KCOEF-VKCOEF*TA)+UBETA(I)*(CB*TA-SB)+P(I)*(CD*TA-
     1   SD)
      A3(I)=TA*TP
      SUMB = SUMB + A2(I)
      GO TO 2
C
C     SIMPLIFIED BISHOP A-TERMS
C
40    A1(I) = CSLICE*DX(I)/CA + TP/CA*(WTT(I)*(1.0-VKCOEF) + P(I)*CD +
     1         UBETA(I)*CB - UALPHA(I)*CA)
      A2(I) = TP*TA
      A3(I) = (WTT(I)*(1.0-VKCOEF) + UBETA(I)*CB + P(I)*CD)*SA
      A4 = (UBETA(I)*SB + P(I)*SD)*(CA-HIGHT(I)/RADIUS)
      A5 = KCOEF*WTT(I)*(CA-HGHTEQ(I)/RADIUS)
      SUMB = SUMB + A3(I) - A4 + A5
    2 CONTINUE
C
C    -----------------------------
C    CALCULATE THE FACTOR OF SAFETY
C    -----------------------------
C
      FOLD=1.5
      DO 10 J=1,10
      SUMT=0.
      DO 6 I=1,NSLICE
      IF(A1(I) .LT. 0.0) A1(I)=0.0
      IF (MB.EQ.1) GO TO 50
      SUMT = A1(I)/(1.0 + A3(I)/FOLD) + SUMT
      GO TO 6
50    SUMT = SUMT + A1(I)/(1.0 + A2(I)/FOLD)
    6 CONTINUE
C                                                                    051486DH
C     ----------------------------------------------                 051486DH
C     CALCULATE CORRECTION FACTOR FOR JANBU CALCULATION               051486DH
C     ----------------------------------------------                 051486DH
C                                                                    051486DH
      F0=1.0                                                         051486DH
      IF(MB.NE.1) F0=CFJ(NCO,NSLICE)                                 051486DH
C                                                                    051486DH
      FNEW= F0 * SUMT/SUMB                                           051486DH
C
C    --------------------
C    CHECK FOR CONVERGENCE
C    --------------------
C
      IF (ABS(FNEW-FOLD).LT..005) GO TO 15
   10 FOLD=FNEW
C
C    ------------------------------
C    STATEMENT OF LACK OF CONVERGENCE
C    ------------------------------
```

```
C
      WRITE(6,103)
  103 FORMAT(//,
     110X,'FACTOR OF SAFETY CALCULATION HAS GONE THROUGH TEN ITERATIONS'
     1//)
      FS=FNEW
      FNEW= 500.
      IF(ISEARC.EQ.0) WRITE(6,101)FS
      IF(ISEARC.EQ.0)GO TO 15
      WRITE(6,104)NSURF
  104 FORMAT(///,
     110X,'THE TRIAL FAILURE SURFACE IN QUESTION IS DEFINED',/,
     110X,'BY THE FOLLOWING',I3,
     1    ' COORDINATE POINTS',///,
     1    12X,'POINT',6X,'X-SURF',6X,'Y-SURF',/
     1    13X,'NO.',8X,'(FT)',8X,'(FT)',/)
      WRITE(6,105)(I,SURF(I,1),SURF(I,2),I=1,NSURF)
  105 FORMAT(12X,I3,2X,2F12.2)
      WRITE(6,101)FS
C
C   ----------------------
C   PRINT FACTOR OF SAFETY
C   ----------------------
C
   15 FS=FNEW
      IF(ISEARC.EQ.1)GO TO 7
      WRITE(6,101)FS
  101 FORMAT(////,10X,'FACTOR OF SAFETY FOR THE PRECEDING SPECIFIED',
     1  ' SURFACE =',F7.3)
      IF(MB.EQ.1) WRITE(6,107)
  107 FORMAT(//,10X,'WARNING - FACTOR OF SAFETY IS CALCULATED BY THE ',
     1    'MODIFIED BISHOP',/,20X,'METHOD. THIS METHOD IS VALID ONLY ',
     1    'IF THE FAILURE SURFACE',/,20X,'APPROXIMATES A CIRCLE.')
      IF(FS.GT.F1)RETURN
      WRITE(6,106)
  106 FORMAT(//,
     110X'***  THE ABOVE FACTOR OF SAFETY IS MISLEADING  ***')
      RETURN
    7 IF(FS.GT.F1)RETURN
      WRITE(6,102)NSURF
      WRITE(6,105)(I,SURF(I,1),SURF(I,2),I=1,NSURF)
  102 FORMAT(//,
     110X'THE FACTOR OF SAFETY FOR THE TRIAL FAILURE SURFACE DEFINED'/
     110X'BY THE COORDINATES LISTED BELOW IS MISLEADING.'///
     110X'FAILURE SURFACE DEFINED BY',I3,' COORDINATE POINTS'///
     112X'POINT',6X,'X-SURF',6X,'Y-SURF',/
     113X'NO.',8X,'(FT)',8X,'(FT)',//)
      WRITE(6,101)FS
      FS= 500.
      RETURN
      END
C
C
```

```
C
      FUNCTION CFJ(NC0,NSLICE)
C
C     CALCULATE F0 CORRECTION FACTOR TO FACTOR OF SAFETY FOR JANBU
C
C     HALL AND HOWARD, MAY 1986; JULY 1986
C
C     B       -- Y-INTERCEPT OF LINE CONNECTING X1,Y1 AND XN,YN
C     M       -- SLOPE OF LINE CONNECTING X1,Y1 AND XN,YN
C     NC0     -- NUMBER OF SLICES FOR WHICH C=0
C     NSLICE -- NUMBEROF SLICES TOTAL
C     NSURF  -- NUMBER OF POINTS DEFINING A TRIAL FAILURE SURFACE
C     SURF   -- COORDINATES DEFINING THE TRIAL FAILURE SURFACE
C
      COMMON /BLK05/NSURF,SURF(100,2)
      REAL M,K
      D=0
      X1=SURF(1,1)
      XN=SURF(NSURF,1)
      Y1=SURF(1,2)
      YN=SURF(NSURF,2)
      M=(YN-Y1)/(XN-X1)
      B=Y1-M*X1
      A=-M
      C=-B
      DENOM=SQRT(A**2.+1.)
      RATIO=FLOAT(NC0)/FLOAT(NSLICE)
      NS=NSURF-1
C
C     FIND LENGTH OF LONGEST CORD D
C
      DO 10 I=2,NS
          DI=ABS(A*SURF(I,1)+SURF(I,2)+C)/DENOM
   10 D=AMAX1(D,DI)
C
C     FIND LENGTH OF CORD L
C
      L=((XN-X1)**2.+ (YN-Y1)**2.)**0.5
      DOVERL = D/L
C
C     DETERMINE WHETHER TO USE K=0.31 (C = 0)
C       OR K=0.50 (C > 0  AND PHI > 0)
C
      K=0.50
      IF(RATIO.GE.0.5) K=0.31
C
C     AND, FINALLY, THE ANSWER ...
C
      CFJ = 1 + K*(DOVERL - 1.4 * DOVERL**2.0)
C
          WRITE(*,*)' JANBU CORRECTION FACTOR IS: ',CFJ
      RETURN
      END
```

Item 11

****

AN INTRODUCTION TO PROBABILISTIC ANALYSIS FOR GEOTECHNICAL ENGINEERING APPLICATIONS AND DECISION MAKING

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U.S.D.A. FOREST SERVICE

GEOTECHNICAL ENGINEERING TRAINING SESSION

OUTLINE OF TOPICS:

A. PROBABILITY AND STATISTICS REFRESHER

1. FUNDAMENTAL PROBABILITY CONCEPTS
2. RANDOM VARIABLES AND PROBABILITY DISTRIBUTIONS
3. GEOTECHNICAL ENGINEERING APPLICATIONS

B. MONTE CARLO SAMPLING AND SIMULATION

1. OVERVIEW OF MONTE CARLO SIMULATION
2. SIMULATION TECHNIQUES
3. EXAMPLES USING THE LEVEL I SLOPE STABILITY ANALYSIS

C. INTRODUCTION TO DECISION ANALYSIS

1. EVALUATION AND COMPARISON OF DECISION ALTERNATIVES
2. THE CONCEPT OF EXPECTED MONETARY VALUE
3. PRELIMINARY ROUTE SELECTION USING LEVEL I FOLLOW-UP
4. EXAMPLES USING THE LEVEL II SLOPE STABILITY ANALYSIS

D. DECISION TREES FOR GEOTECHNICAL PROJECTS

1. CONSTRUCTION AND USE OF DECISION TREES
2. CONDITIONING AND UPDATING GEOTECHNICAL UNCERTAINTIES
3. EXAMPLE ANALYSIS OF ROCK AGGREGATE SOURCES

PROBABILITY AND STATISTICS REFRESHER

PROBABILITY THEORY: AN INTERNALLY CONSISTENT BRANCH OF MATHEMATICAL LOGIC, CONSISTING OF A SYSTEMATIC STATEMENT AND FORMULATION OF PRINCIPLES THAT NECESSARILY FOLLOW FROM A LIMITED SET OF FUNDAMENTAL AXIOMS.

PROBABILITY CONCEPTS ARE RELATED CLOSELY TO SIMILAR IDEAS FOUND IN SET THEORY.

SET THEORY	PROBABILITY CONCEPTS
SPACE S, LARGEST SET CONTAINING ALL ELEMENTS OF ALL SETS UNDER CONSIDERATION	SAMPLE SPACE (SURE EVENT)
ELEMENTS a, b, ...	SAMPLE POINTS (POSSIBLE OUTCOMES OR OCCURRENCES)
SETS A, B, ... (SUBSETS OF S)	EVENTS (COLLECTIONS OF ONE OR MORE SAMPLE POINTS)
EMPTY SET	IMPOSSIBLE EVENT
B	EVENT B OCCURS
$\overline{B}$ (COMPLEMENT OF B)	EVENT B DOES NOT OCCUR
A U B	EVENT A OCCURS, OR EVENT B OCCURS, OR BOTH OCCUR
AB	BOTH EVENTS A AND B OCCUR
AB = EMPTY SET	EVENTS A AND B ARE MUTUALLY EXCLUSIVE (THEY CANNOT OCCUR SIMULTANEOUSLY)

IN PROBABILITY THEORY IT IS ASSUMED THAT A RANDOM EXPERIMENT, OR SAMPLING EXERCISE, WILL HAVE OUTCOMES (OR SAMPLE POINTS) THAT DEPEND ON CHANCE. A COLLECTION OF ONE OR MORE OUTCOMES IS KNOWN AS AN EVENT.

EXAMPLE

CONSIDER A LABORATORY TESTING PROGRAM WHEREIN THE DRY UNIT WEIGHT IS DETERMINED FOR EACH OF 10 SOIL SPECIMENS RANDOMLY SELECTED FROM A SHELBY TUBE SAMPLE. AN OUTCOME (OR SAMPLE POINT) IS EQUIVALENT TO ONE TEST RESULT (SAY, 1.68 TCM). AN EVENT IS A COLLECTION OF OUTCOMES, SUCH AS ALL TEST RESULTS GREATER THAN 1.72 TCM, OR ALL RESULTS BETWEEN 1.6 AND 1.7 TCM.

DEFINE $P(B)$ AS THE PROBABILITY OF EVENT B.

$P(B)$ IS A FINITE NUMBER ASSIGNED TO EVENT B, AND THUS CAN BE THOUGHT OF AS A PROBABILITY FUNCTION WHOSE VALUE IS A FUNCTION OF THE EVENT B.

THE ASSIGNMENT OF PROBABILITY VALUES TO EVENTS USUALLY IS BASED ON:

1. RELATIVE FREQUENCY OF OBSERVED OCCURRENCES
   (BASED ON SAMPLING HISTORY AND PAST EXPERIENCES; I.E., "HARD" FACTS OR INFORMATION)

2. RELATIVE SUBJECTIVE LIKELIHOOD
   (BASED ON AVAILABLE INFORMATION, PROFESSIONAL JUDGMENT, COMMON SENSE; I.E., "SOFT" INFORMATION)

AXIOMS OF PROBABILITY

1. $0 \leq P(B) \leq 1$ (FOR ANY EVENT B IN THE SAMPLE SPACE)

2. $P(S) = 1$ (S IS THE SAMPLE SPACE)

3. IF $A_1, A_2, \ldots A_N$ ARE MUTUALLY EXCLUSIVE EVENTS IN S, THEN

$$P(A_1 \cup A_2 \cup \ldots \cup A_N) = P(A_1) + P(A_2) + \ldots + P(A_N)$$

IMPORTANT PROPERTIES AND RELATIONSHIPS

1. $P(A) = 1 - P(\bar{A})$ FOR ANY EVENT A IN S

2. IF EVENT A IS CONTAINED IN EVENT C (A IS A SUBEVENT OF C), THEN

$$P(A) \leq P(C)$$

3. ADDITION THEOREM:

$$P(A \cup B) = P(A) + P(B) - P(AB)$$ FOR ANY EVENTS A AND B IN S

4. DEFINITION: TWO EVENTS A AND B ARE SAID TO BE INDEPENDENT IF AND ONLY IF

$$P(AB) = P(A)P(B)$$

CONDITIONAL PROBABILITY

THE **CONDITIONAL PROBABILITY** OF EVENT A, GIVEN THAT EVENT B HAS OCCURRED, IS DEFINED AS

$$P(A|B) = \frac{P(AB)}{P(B)} \qquad \text{FOR } P(B) \neq 0$$

ALSO, NOTE THAT $P(AB) = P(A|B)P(B) = P(B|A)P(A)$

(THIS IS SOMETIMES CALLED THE MULTIPLICATION THEOREM)

IF EVENTS A AND B ARE INDEPENDENT, THEN A DOES NOT DEPEND ON B AND $P(A|B) = P(A)$. LIKEWISE, B DOES NOT DEPEND ON A AND $P(B|A) = P(B)$. ALSO, EACH EVENT IS INDEPENDENT OF THE OTHER'S COMPLEMENT, AND THE TWO COMPLEMENTS ARE INDEPENDENT.

THEOREM OF TOTAL PROBABILITY:

FOR EVENTS $B_1, B_2, \ldots, B_N$ THAT ARE MUTUALLY EXCLUSIVE AND EXHAUSTIVE (I.E., $B_1 + B_2 + \ldots + B_N = S$), THE PROBABILITY OF ANY ARBITRARY EVENT A IN S IS GIVEN BY

$$P(A) = \sum^{N} P(A|B_i)P(B_i)$$

EXAMPLE

OUR HISTORICAL RECORDS OF CONTRACT BIDDING FOR ROAD/BRIDGE CONSTRUCTION INDICATE THAT TWO CONTRACTORS (C1 AND C2) HAVE ABOVE AVERAGE PERFORMANCE IN SUBMITTING ACCEPTABLE BIDS. FOR 19 BIDDED PROJECTS, 4 OF 5 BIDS FROM C1 WERE OK, 5 OF 6 BIDS FROM C2 WERE OK, AND 5 OF 8 BIDS FROM OTHER CONTRACTORS (C3) WERE OK. ASSUMING THE SAME FIELD OF CONTRACTORS WILL BID ON OUR NEXT PROJECT, WHAT IS THE PROBABILITY THAT WE WILL RECEIVE AN ACCEPTABLE (OK) BID?

LET: C_1 = EVENT THAT C1 SUBMITS A BID; $P(C_1) = 5/19$
C_2 = EVENT THAT C2 SUBMITS A BID; $P(C_2) = 6/19$
C_3 = EVENT THAT OTHERS SUBMIT BID; $P(C_3) = 8/19$
A = EVENT THAT ACCEPTABLE BID IS SUBMITTED

$$P(A) = P(A|C_1)P(C_1) + P(A|C_2)P(C_2) + P(A|C_3)P(C_3)$$

$$= .80(.263) + .833(.316) + .625(.421) = .737$$

BAYES' THEOREM:

FOR ANY TWO ARBITRARY EVENTS A AND B WITH $P(A) \neq 0$ AND $P(B) \neq 0$,

$$P(B|A) = \frac{P(A|B)P(B)}{P(A)}$$

IN ADDITION, FOR A SET OF MUTUALLY EXCLUSIVE, EXHAUSTIVE EVENTS B_i, THE ABOVE RELATION CAN BE EXPRESSED AS

$$P(B_k|A) = \frac{P(A|B_k)P(B_k)}{\sum^{N} P(A|B_i)P(B_i)}$$

THIS THEOREM ALLOWS THE POSTERIOR PROBABILITY $P(B|A)$ TO BE EVALUATED IN TERMS OF THE PRIOR INFORMATION GIVEN BY $P(B)$ AND $P(A|B)$.

EXAMPLE (CONTINUED)

GIVEN THAT AN ACCEPTABLE BID IS RECEIVED, WHAT IS THE PROBABILITY THAT ONE OF THE ABOVE-AVERAGE CONTRACTORS (C1 OR C2) DID NOT SUBMIT IT?

$$P(C_3|A) = \frac{.625(.421)}{.737} = .357$$

THUS, GIVEN THAT AN ACCEPTABLE BID IS RECEIVED, THE PROBABILITY THAT ONE OF THE ABOVE-AVERAGE CONTRACTORS DID SUBMIT IT IS GIVEN BY:

$$1 - .357 = .643$$

RANDOM VARIABLES AND PROBABILITY DISTRIBUTIONS

DEFINITION:

A **RANDOM VARIABLE** IS A VARIABLE (SUCH AS A PHYSICAL PROPERTY OR CHARACTERISTIC) THAT TAKES ON DIFFERENT VALUES ACCORDING TO THE OUTCOMES OF REPEATED EXPERIMENTS OR SAMPLING EVENTS.

THESE VALUES CANNOT BE PREDICTED WITH CERTAINTY; THUS, EACH POSSIBLE VALUE OR RANGE OF VALUES HAS AN ASSOCIATED PROBABILITY (OR LIKELIHOOD) OF OCCURRENCE. FOR THIS REASON, RANDOM VARIABLES OFTEN ARE CALLED **STOCHASTIC VARIABLES** TO INDICATE THE STOCHASTIC, OR PROBABILISTIC, NATURE OF THEIR VALUES. THE TERM "RANDOM" HERE DOES NOT IMPLY THAT THE VARIABLE ITSELF IS RANDOM OR HAS RANDOMLY DISTRIBUTED VALUES, BUT RATHER THAT THE VALUES OCCUR IN A PROBABILISTIC MANNER.

IF THE VALUE OF A VARIABLE IS KNOWN WITH CERTAINTY OR WITH NEGLIBLE UNCERTAINTY (AT THE TIME OF ANALYSIS OR DECISION MAKING), THEN THE VARIABLE IS CALLED A **DETERMINISTIC VARIABLE**.

DEFINITION:

A PROBABILITY DISTRIBUTION IS A FUNCTION, EITHER DISCRETE OR CONTINUOUS, THAT DEFINES PROBABILITIES OF OCCURRENCE FOR VALUES OF A RANDOM VARIABLE.

1. THE **CUMULATIVE DISTRIBUTION FUNCTION** FOR A RANDOM VARIABLE X IS GIVEN BY:

lower case is an actual number

$$F(x) = P(X \text{ TAKES ON A VALUE} \leq x) = P(X \leq x)$$

PROPERTIES OF A CDF:

A. IT HAS VALUES BETWEEN 0 AND 1 INCLUSIVE AND CAN BE DEFINED FOR DISCRETE OR CONTINUOUS RANDOM VARIABLES.

B. IT IS A NON-NEGATIVE, NON-DECREASING FUNCTION OF A REAL-VALUED VARIABLE.

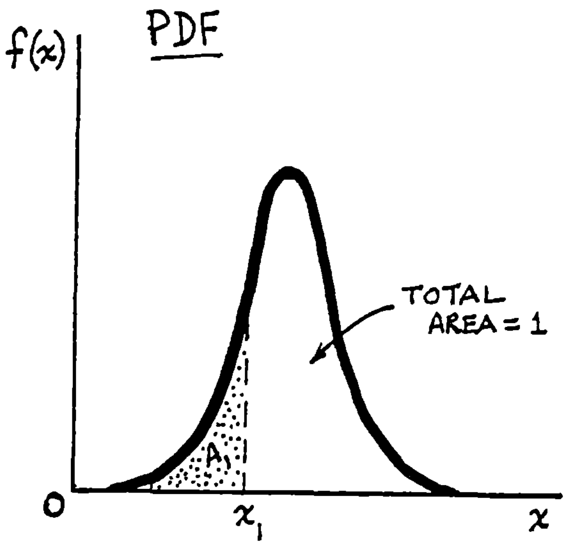
C. FOR VALUES a AND b OF A R.V. X, SUCH THAT $a < b$,
$$P(a < X \leq b) = F(b) - F(a)$$

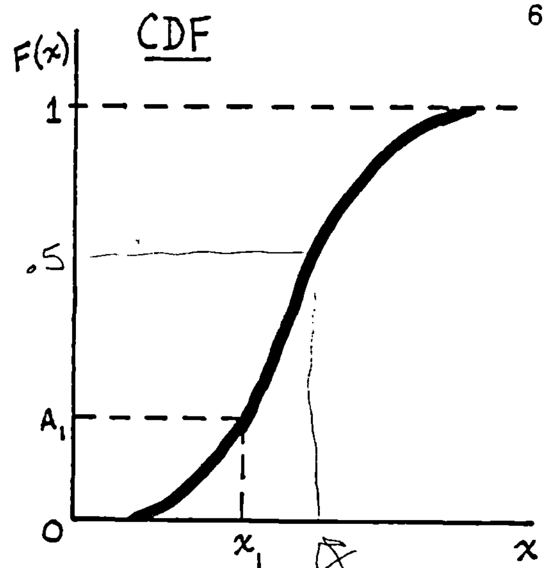
2. THE **PROBABILITY DENSITY FUNCTION** FOR A CONTINUOUS R.V. X IS DEFINED AS:
$$f(x) = \frac{d[F(x)]}{dx}$$

PROPERTIES OF A PDF:

A. IT IS A NON-NEGATIVE FUNCTION WHERE $\int_{-\infty}^{\infty} f(x)dx = 1$.

B. $P(a < X \leq b) = \int_a^b f(x)dx$





median is 50% value
not the same

EXPECTATION OPERATOR

THE EXPECTATION OF A R.V. (random variable) X IS DEFINED AS:

$$E[X] = \int_{\text{all } x} x \, f(x) dx$$

THIS EXPECTATION ALSO IS KNOWN AS THE **MEAN** OF X: $m(X) = E[X]$, AND IT DEFINES THE "CENTROIDAL AXIS" OF THE PDF OF X.

A COMMON MEASURE OF THE DISPERSION OF THE DISTRIBUTION OF X ABOUT ITS MEAN IS GIVEN BY THE **VARIANCE** OF X:

$$var(X) = \int_{\text{all } x} [x - m(x)]^2 \, f(x) dx$$

<u>IMPORTANT RELATIONSHIPS</u>

1. FOR A CONSTANT c AND R.V. X: $E[cX] = cE[X]$

$$var(X+c) = var(X)$$

$$var(cX) = c^2 var(X)$$

2. FOR TWO RANDOM VARIABLES X AND Y: $E(X+Y) = E(X) + E(Y)$

3. $var(X) = E(X^2) - [m(X)]^2$

4. THE STANDARD DEVIATION OF X IS THE POSITIVE SQUARE ROOT OF THE VARIANCE OF X:

$$sd(X) = \sqrt{var(X)}$$

5. THE COVARIANCE BETWEEN TWO RANDOM VARIABLES X AND Y IS:

$$cov(X,Y) = E\{[X - m(X)][Y - m(Y)]\}$$

EXAMPLES OF USEFUL PDF'S

RELATIVE-FREQUENCY HISTOGRAM

$$m(x) = \frac{1}{n}\sum_{i=1}^{k} f_i x_i$$

$$v(x) = \frac{1}{n-1}\left[\sum^{k} f_i x_i^2 - \frac{\left(\sum^{k} f_i x_i\right)^2}{n}\right]$$

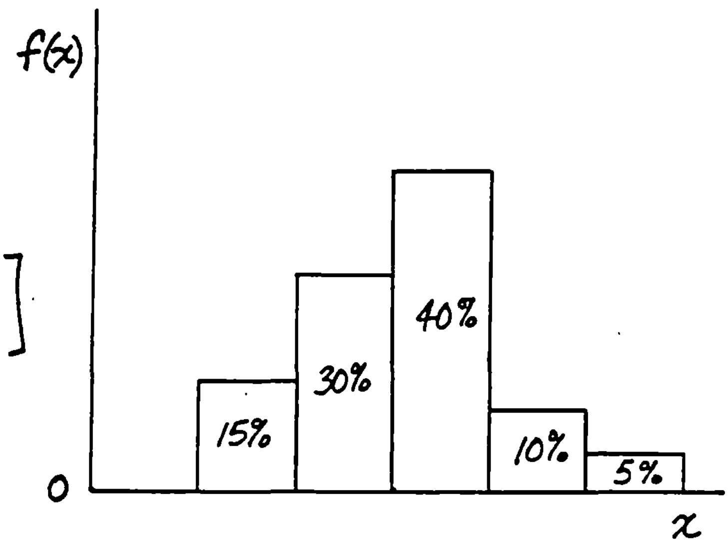
where:

n = no. of data = 100

k = no. of classes

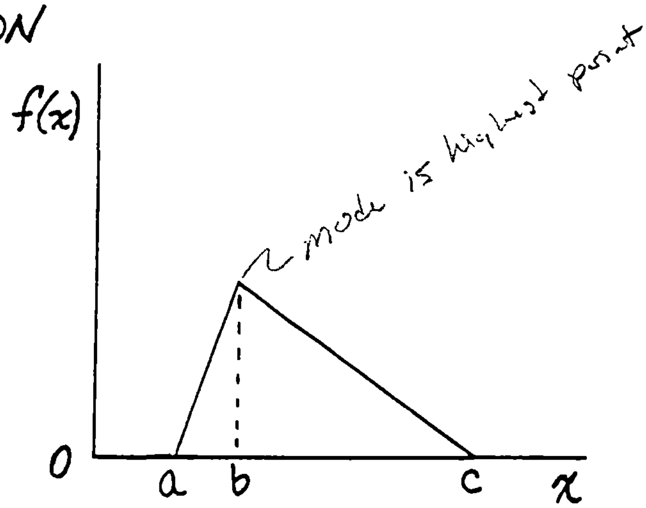
f_i = no. of observations (percent) in the i-th class

x_i = midpoint of i-th class



TRIANGULAR DISTRIBUTION

$$f(x) = \begin{cases} \dfrac{2(x-a)}{(c-a)(b-a)}, & \text{if } a \le x \le b \\ \dfrac{2(c-x)}{(c-a)(c-b)}, & \text{if } b \le x \le c \\ 0, & \text{otherwise} \end{cases}$$

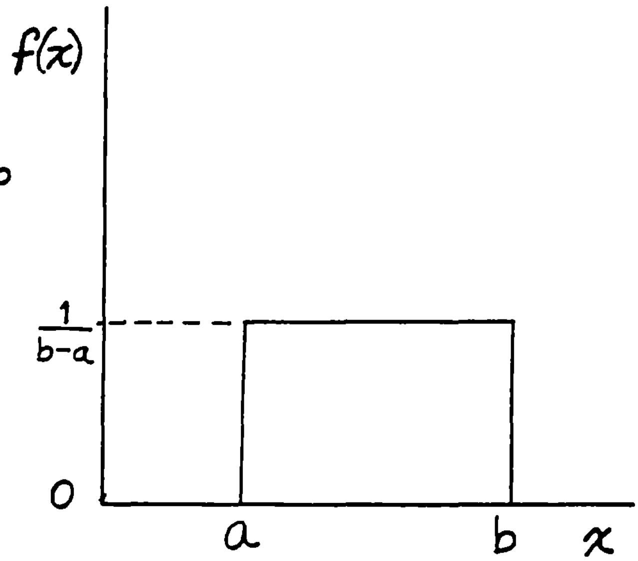


$$m(x) = \frac{a+b+c}{3}$$

$$v(x) = \frac{a(a-b) + b(b-c) + c(c-a)}{18}$$

UNIFORM DISTRIBUTION

$$f(x) = \begin{cases} \frac{1}{b-a}, & \text{if } a \le x \le b \\ 0, & \text{otherwise} \end{cases}$$

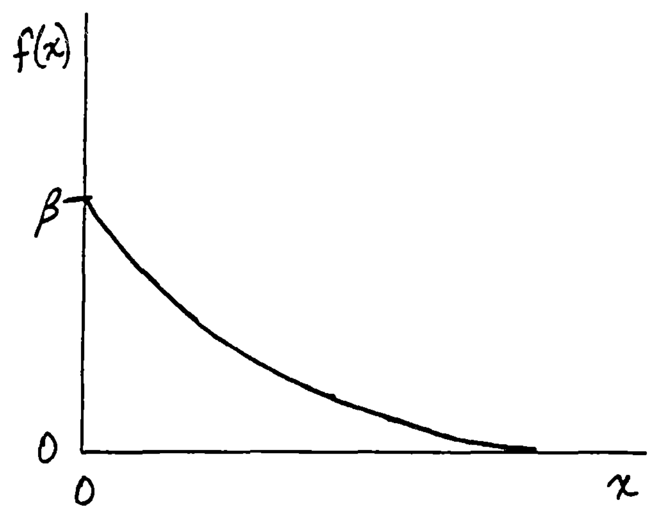


$$m(x) = \frac{a+b}{2}$$

$$v(x) = \frac{(b-a)^2}{12}$$

EXPONENTIAL DISTRIBUTION

$$f(x) = \begin{cases} \beta e^{-\beta x}, & \text{if } x \ge 0 \\ 0, & \text{otherwise} \end{cases}$$

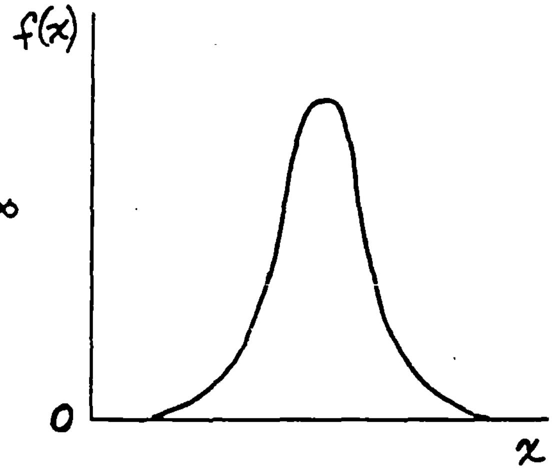


$$m(x) = \frac{1}{\beta}$$

$$v(x) = \frac{1}{\beta^2}$$

NORMAL (GAUSSIAN) DISTRIBUTION

$$f(x) = \frac{e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}}{\sigma\sqrt{2\pi}}, \text{ for } -\infty < x < \infty$$



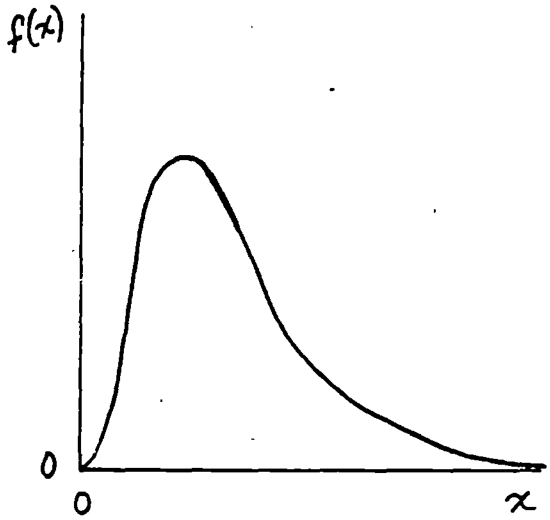
$$m(x) = \mu$$

$$v(x) = \sigma^2$$

LOGNORMAL DISTRIBUTION

(for a RV X such that $\ln X$ has a normal distr.)

$$f(x) = \begin{cases} \dfrac{e^{-\frac{1}{2}\left(\frac{\ln x-\mu}{\sigma}\right)^2}}{x\sigma\sqrt{2\pi}}, & \text{if } x>0 \\ 0, & \text{otherwise} \end{cases}$$



$$m(x) = e^{\mu + \frac{\sigma^2}{2}}$$

$$v(x) = [m(x)]^2\left(e^{\sigma^2} - 1\right)$$

Also, $\mu = \ln[m(x)] - \frac{\sigma^2}{2}$

$$\sigma^2 = \ln\left\{\frac{v(x)}{[m(x)]^2} + 1\right\}$$

Beta Distribution

$$f(x) = \begin{cases} \dfrac{\Gamma(P+Q)}{\Gamma(P)\Gamma(Q)}\left[\dfrac{(x-a)^{P-1}(b-x)^{Q-1}}{(b-a)^{P+Q-1}}\right], & \text{if } a \le x \le b \\ 0, & \text{otherwise} \end{cases}$$

for $P > 0$, $Q > 0$

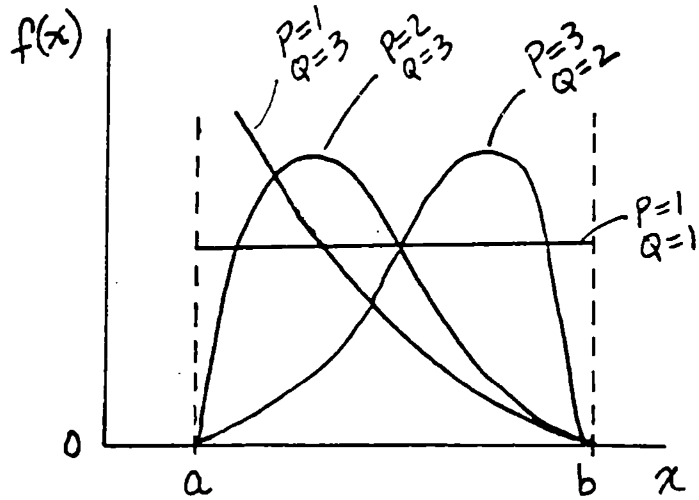
$\Gamma(a)$ = value of complete gamma function with argument a

$$= \int_0^\infty u^{a-1} e^{-u}\, du \quad = (a-1)\Gamma(a-1)$$

When a = positive integer, then $\Gamma(a) = (a-1)!$

$$m(x) = \frac{aQ + bP}{P+Q}$$

$$v(x) = \frac{(b-a)^2 PQ}{(P+Q)^2(P+Q+1)}$$



This is a very flexible pdf over a defined finite interval.

EXAMPLES:

1. Measured values of moisture content in a certain soil appear to be uniform-distributed over the range of 8 to 26 percent.

a) Find the mean and sd of moisture content.
[Note: the cdf is $F(x) = \frac{x-a}{b-a}$, for $a \le x \le b$]

$$m_x = \frac{8+26}{2} = \underline{17\%} \qquad sd_x = \sqrt{\frac{(26-8)^2}{12}} = \underline{5.2\%}$$

b) Find the probability that moisture content is less than 15%.

$$P[X \le 15] = \frac{15-8}{26-8} = \underline{0.39}$$

c) Find the prob. that moisture content is between 16 & 20%.

$$P[16 \le X \le 20] = \frac{20-8}{26-8} - \frac{16-8}{26-8} = \underline{0.22}$$

2. A sample of dry unit weights of a given soil appears to be beta-distributed over the range of 1.6 to 1.9 tcm, with parameters $P=1$, $Q=2$.

a) What is the mean dry unit weight? $m_x = \frac{1.6(2)+1.9(1)}{3} = \underline{1.7}$ tcm

b) What is the prob. that dry unit wt. exceeds 1.8 tcm?

$$P[X>1.8] = \int_{1.8}^{1.9} \frac{\Gamma(3)}{\Gamma(1)\Gamma(2)} \left[\frac{(x-1.6)^0(1.9-x)^1}{(1.9-1.6)^2}\right] dx$$

$$= \frac{2}{.09}\left[-\frac{1}{2}(1.9-x)^2\right]_{1.8}^{1.9} = -16.67\left[0-0.1^2\right]$$

$$= \cancel{0.167}\ \underline{0.111}$$

MONTE CARLO SIMULATION

LET'S ASSUME WE ARE INTERESTED IN DESCRIBING OR PREDICTING A PHYSICAL PROPERTY OR CHARACTERISTIC THAT CAN NOT BE SAMPLED DIRECTLY, BUT CAN BE EXPRESSED AS A MATHEMATICAL FUNCTION OF PROPERTIES THAT CAN BE SAMPLED, OR AT LEAST CAN BE DESCRIBED IN SOME RATIONAL MANNER.

A GOOD EXAMPLE OF SUCH A SITUATION IS THE SAFETY FACTOR, WHICH IS CALCULATED IN LIMITING-EQUILIBRIUM ANALYSES:

$$SF = Fn(X_1, X_2, \ldots, X_n)$$

WHERE n IS THE NUMBER OF X_i INPUT PROPERTIES (OR PARAMETERS).

ANY OF THE X_i'S CAN BE CONSIDERED AS CONSTANT (DETERMINISTIC) IF WARRANTED BY ITS NATURAL, PHYSICAL CHARACTER. HOWEVER, IN MOST GEOLOGICAL AND GEOTECHNICAL ENGINEERING STUDIES, MOST (IF NOT ALL) OF THE X_i'S HAVE SUFFICIENT SPATIAL VARIABILITY AND MEASUREMENT UNCERTAINTY TO WARRANT THEM BEING TREATED AS **RANDOM VARIABLES**. EXAMPLES OF SUCH RANDOM VARIABLES INCLUDE:

SHEAR STRENGTH (COHESION AND FRICTION ANGLE)
UNIT WEIGHT
MOISTURE CONTENT
PORE PRESSURE DUE TO WATER
SITE GEOMETRY (THICKNESS OF GEOLOGIC UNITS, SLOPE ANGLE, ETC)

IF WE WANT TO PREDICT A POSSIBLE VALUE OF THE OUTPUT VARIABLE (SAFETY FACTOR, HERE IN OUR EXAMPLE), WE TAKE A POSSIBLE VALUE FOR EACH INPUT VARIABLE AND USE THE FUNCTION (LIMITING EQUIL.) FORMULA TO CALCULATE THE CORRESPONDING VALUE OF THE OUTPUT VARIABLE. THIS IS KNOWN AS ONE **MONTE CARLO** PASS, OR ITERATION.

THE ESSENCE OF MONTE CARLO SIMULATION IS TO GENERATE A CONSIDERABLE NUMBER OF OUTPUT VALUES (SAY, 100 OR MORE) BY REPEATED RANDOM, INDEPENDENT SAMPLING OF A SET OF POSSIBLE INPUT VALUES AND THEN CALCULATING A CORRESPONDING OUTPUT VALUE FOR EACH REPEAT. THE RESULT IS A NUMBER OF POSSIBLE OUTPUT VALUES, WHICH CAN BE DISPLAYED IN A HISTOGRAM AND TREATED AS A SET OF POSSIBLE REALIZATIONS OF THE OUTPUT VARIABLE. THE COMPUTATIONAL PROCEDURE MIGHT LOOK SOMETHING LIKE THIS:

INPUT PROBABILITY DISTR. FOR EACH INPUT RV	→	SAMPLE A VALUE FROM THE PROB. DISTR. OF EACH RV
repeat for another simulation pass ↗		↓
STORE CALCULATED VALUE OF THE OUTPUT RV	←	USE DEFINED FORMULA TO CALCULATE THE VALUE OF THE OUTPUT RV

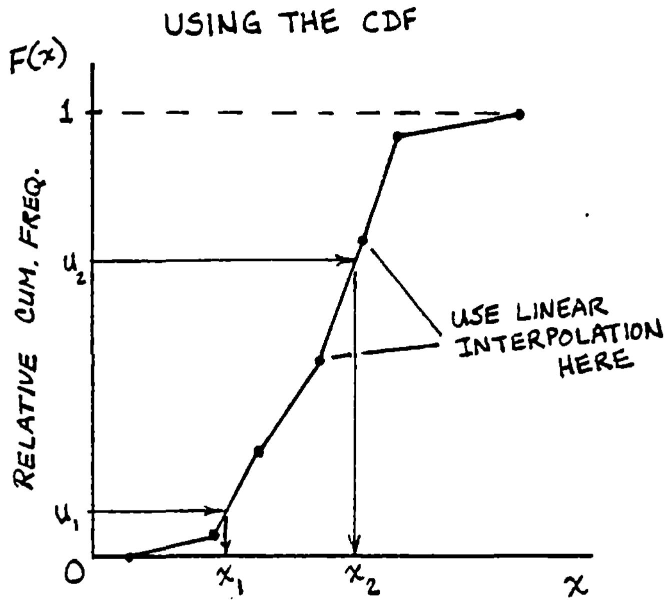
THERE ARE NO DEFINITIVE RULES THAT DICTATE HOW MANY SIMULATION PASSES ARE REQUIRED IN ANY MONTE CARLO SIMULATION STUDY. THE NUMBER OF PASSES NECESSARY TO PROVIDE CONSISTENT, STABLE RESULTS IS A FUNCTION OF: THE NUMBER OF INPUT RV'S, THE SHAPES AND RANGES OF THE PROB. DISTRIBUTIONS OF INPUT RV'S, AND THE RELATIONSHIP OR FUNCTION THAT TIES ALL THE INPUT TERMS TOGETHER.

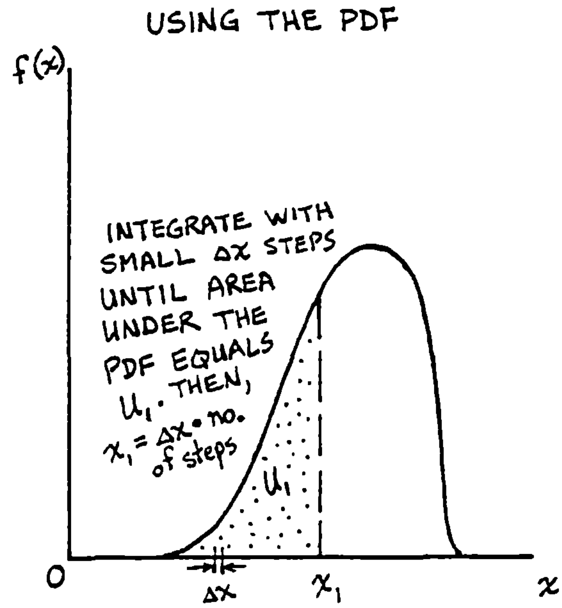
SAMPLING FROM PROBABILITY DISTRIBUTIONS

VARIOUS NUMERICAL AND COMPUTER-BASED **SAMPLING PROCEDURES** ARE AVAILABLE FOR SAMPLING FROM PROBABILITY DISTRIBUTIONS. PSUEDO-RANDOM, INDEPENDENT VALUES OF RV'S DEFINED BY COMMON TYPES OF PDF'S (SUCH AS UNIFORM, NORMAL, LOGNORMAL, EXPONENTIAL) CAN BE GENERATED USING PROCEDURES DESCRIBED IN REFERENCES LIKE THE **HANDBOOK OF MATHEMATICAL FUNCTIONS** (ED. BY ABRAMOWITZ AND STEGUN, 1965), CHAPTER 26.

IN THE MOST BASIC CONTEXT, ANY RV WHOSE CDF OR PDF CAN BE DESCRIBED MATHEMATICALLY CAN BE RANDOMLY SAMPLED. IF THE CDF IS KNOWN, THEN A UNIFORM [0,1] NUMBER IS SIMULATED FIRST AND THEN USED IN AN INVERSE FASHION (I.E., Y TO X) TO PROVIDE A SIMULATED VALUE OF THE RV. IF THE CDF IS DEFINED BY A DATA-DERIVED CUMULATIVE-FREQUENCY PLOT, THEN THE INVERSE PROCEDURE CONSISTS OF A SIMPLE LINEAR OR CUBIC-SPLINE INTERPOLATION (BETWEEN TWO POINTS OF THE CUM-FREQ PLOT).

WHEN THE CDF INVERSE RELATIONSHIP IS NOT EASILY OBTAINED, THEN THE PDF CAN BE USED IN A NUMERICAL INTEGRATION SCHEME TO PROVIDE A SIMULATED VALUE OF THE RV.





IF ANY TWO RANDOM VARIABLES ARE CORRELATED (I.E., THEY ARE NOT INDEPENDENT OF EACH OTHER), THEN THE CORRELATION SHOULD BE ACCOUNTED FOR DURING EACH SIMULATION PASS IN ORDER TO PROVIDE ONLY REALISTIC OUTCOMES. THERE ARE SEVERAL WAYS IN WHICH THIS CORRELATION CAN BE INCLUDED IN THE SIMULATION SCHEME:

1. APPROXIMATE METHODS

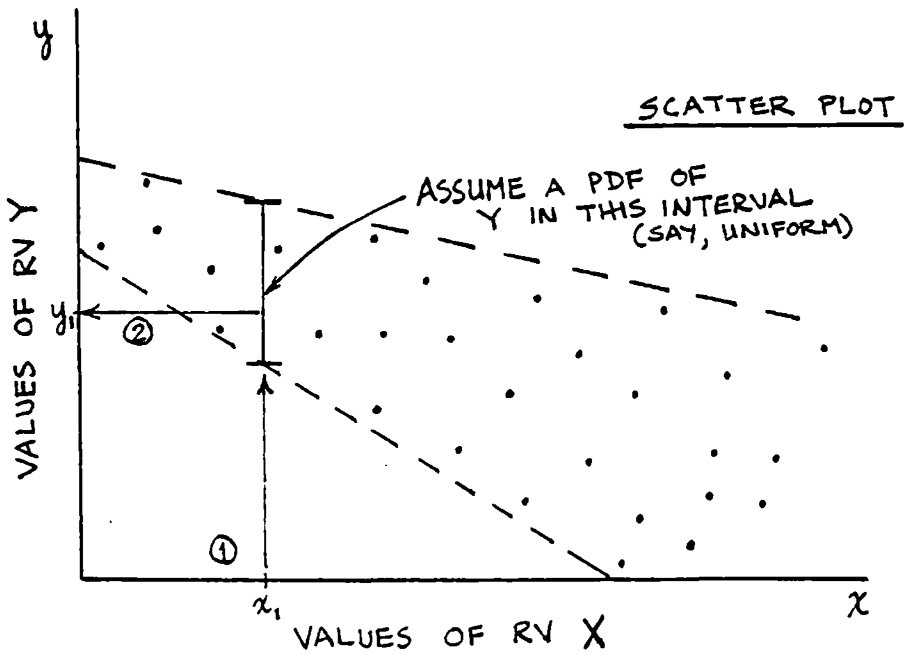
A. IF ONE RV IS PROPORTIONAL TO THE OTHER (POSITIVE CORRELATION), THEN THE SAME INITIAL RANDOM NUMBER (UNIFORM: [0,1]) IS USED TO SAMPLE FROM THE PROB. DISTRIBUTIONS OF BOTH RV'S.

B. IF ONE RV IS INVERSELY PROPORTIONAL TO THE OTHER (NEGATIVE CORRELATION), THEN THE COMPLEMENT (1-U) OF THE RANDOM NUMBER, U, USED TO SAMPLE THE PROB. DISTR. OF THE FIRST RV IS USED TO SAMPLE THE PROB. DISTR. OF THE SECOND RV.

2. MORE EXACT METHODS

A. THE COVARIANCE STRUCTURE BETWEEN TWO RV'S CAN BE PRESERVED IN A SIMULATION BY MATHEMATICAL TECHNIQUES, PROVIDED THAT THE COVARIANCE OR CORRELATION COEFFICIENT BETWEEN THE TWO RV'S IS KNOWN AND THAT THE PDF'S OF THE TWO RV'S ARE AMENABLE TO THE TECHNIQUES.

B. USING A MATHEMATICAL RELATIONSHIP (FUNCTION OR EQUATION) DEFINED FOR THE TWO RV'S FROM A SCATTER PLOT, A TWO-STAGE MONTE CARLO SAMPLING IS ACCOMPLISHED VIA A CONTROLLED, DEPENDENT SAMPLING OF THE SECOND RV, GIVEN THE VALUE THAT HAS BEEN PREVIOUSLY SAMPLED FOR THE FIRST RV.



LANDSLIDE HAZARD ASSESSMENT, OR —

SLOPE RELIABILITY ANALYSIS

A SLOPE RELIABILITY ANALYSIS CONSISTS OF USING PROBABILISTIC MODELS TO DEDUCE IN A QUANTIFIED MANNER THE UNCERTAINTIES ASSOCIATED WITH PREDICTIONS OF SLOPE STABILITY (BEHAVIOR). THESE UNCERTAINTIES TYPICALLY ARE BUNDLED INTO AN ESTIMATE OF SLOPE INSTABILITY, KNOWN AS THE **PROBABILITY OF SLOPE FAILURE.**

IF A GIVEN SLOPE HAS AN ESTIMATED PROBABILITY OF FAILURE EQUAL TO 0.35, THEN THE SLOPE RELIABILITY IS EQUAL TO 0.65. THUS, THE UNCERTAINTY IN HOW A SLOPE WILL BEHAVE IS INCORPORATED INTO THIS ONE TERM, THE PROBABILITY OF FAILURE.

IN MANY SLOPE RELIABILITY STUDIES, THE PROBABILITY OF FAILURE IS OBTAINED VIA SYSTEMATIC CALCULATIONS WHEREBY UNCERTAINTIES ON INPUT VARIABLES (PROPERTIES OR PARAMETERS) ARE PROPAGATED TO UNCERTAINTIES ON A PREDICTION OF SLOPE STABILITY. THIS PROPAGATION SCHEME OFTEN IS BASED ON MONTE CARLO SIMULATION, AND THE PREDICTION OF SLOPE STABILITY IS GIVEN BY THE PROBABILITY OF FAILURE, WHICH IS THE PERCENT OF SIMULATED FACTORS OF SAFETY THAT ARE LESS THAN ONE.

RISK ANALYSIS

THE RESULTS OF A RELIABILITY ANALYSIS OR HAZARD ASSESSMENT CAN BE INCORPORATED INTO A SOCIO-ECONOMIC FRAMEWORK TO PROVIDE A SYSTEM FOR EVALUATING PERTINENT SOCIAL OR ECONOMIC RISKS. THE IMPLEMENTATION OF SUCH A SYSTEM IS KNOWN AS RISK ANALYSIS.

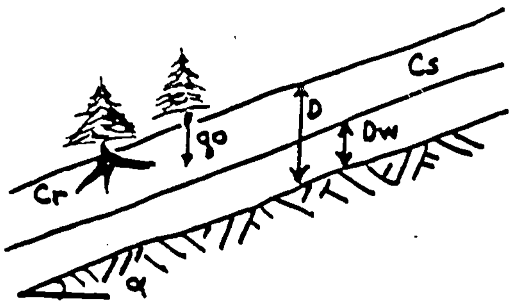
IT IS IMPORTANT TO DISTINGUISH BETWEEN HAZARD ASSESSMENT AND RISK ASSESSMENT. THE FORMER IS CONDUCTED PRIMARILY BY SCIENTISTS AND ENGINEERS, WHEREAS THE LATTER IS INFLUENCED HEAVILY BY MANAGERS, POLITICIANS, AND THE PUBLIC. TWO AREAS MAY HAVE SIMILAR PREDICTED HAZARDS, BUT HAVE ENTIRELY DIFFERENT RISKS. FOR EXAMPLE, TWO AREAS MAY HAVE SIMILAR PROBABILITIES OF SLOPE FAILURE, BUT ONE MAY HAVE A MUCH HIGHER ASSOCIATED RISK DUE TO GREATER POTENTIAL OF LOSING RECREATION, TIMBER, OR A MAJOR ACCESS ROUTE.

DECISION ANALYSIS IS AN EXTENSION OF RISK ANALYSIS WHEREIN THE EVALUATED RISKS OF VARIOUS DECISION ALTERNATIVES ARE COMPARED TO PROVIDE INPUT FOR DECISION MAKING. A DECISION ANALYSIS REQUIRES THAT VALUES (MONETARY OR OTHERWISE) BE PLACED ON CONSEQUENCES OF THE DECISION ALTERNATIVES; THUS, IT IS ALMOST ALWAYS PROJECT SPECIFIC.

LEVEL I STABILITY ANALYSIS

The Level I Stability Analysis (LISA) program uses the infinite slope equation to calculate factor of safety (Figure 1). Values for each variable in the equation, except for soil shear strength (TAU), are sampled from a probability distribution selected by the user. The user may choose between a constant value or uniform, normal, lognormal, triangular, beta or histogram distributions, and enters the parameter values necessary to define the distribution (Figure 2).

Soil shear strength is handled somewhat differently to account for the inverse relationship between soil cohesion (Cs) and friction angle (PHI). The user selects distributions for PHI and Cs, but LISA does not sample values of PHI and Cs directly. Rather the mean and standard deviation of each is calculated and used, along with effective normal stress, to calculate the mean and variance of shear strength (TAU) (Figure 1). LISA first samples for each of the other input variables to calculate the effective normal stress. Values of TAU are then simulated from a lognormal distribution to prevent negative shear strengths from being sample. The user must also enter a value for the correlation coefficient of Cs and tan(PHI) which is used to calculate the covariance between Cs and tan(PHI). Values of -0.6 to -0.8 are reasonable values to use if no data are available. [Note: if all soil cohesion is due to apparent cohesion, r may be taken as 0.] Figure 3 illustrates that the correlation coefficient acts to reduce the variance of TAU.



$$F.S. = \frac{Cr + TAU}{\sin\alpha \cos\alpha \left[q_o + \gamma(D - D_w) + \gamma_{SAT} D_w\right]}$$

$$E[TAU] = E[Cs] + \sigma'_n E[\tan\phi]$$

$$Var[TAU] = Var[Cs] + \sigma'^2_n Var[\tan\phi] + 2\,Cov[c, \tan\phi]$$

$$Cov[c, \tan\phi] = r * s(C_s) * s(\tan\phi)$$

$$\sigma'_n = \cos^2\alpha \left[q_o + \gamma(D - D_W) + (\gamma_{SAT} - \gamma_w) D_w\right]$$

Values of TAU are simulated from a Lognormal pdf.

FIGURE 1

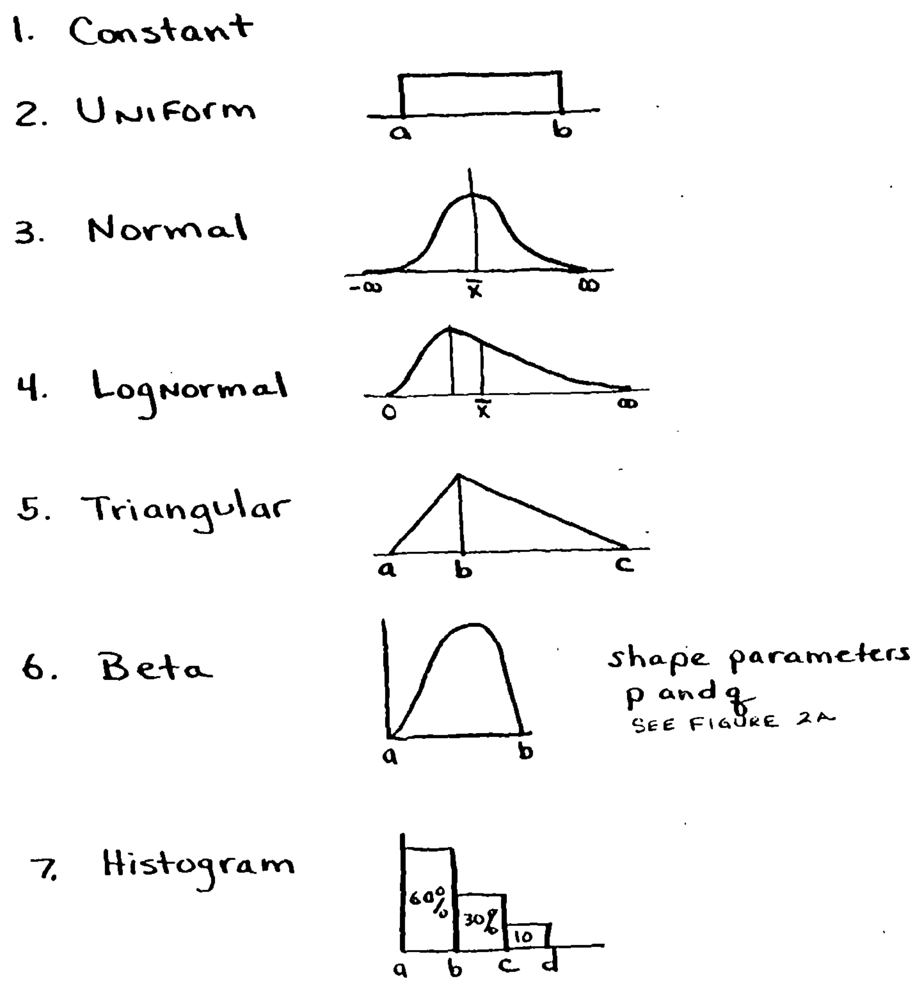


FIGURE 2 pdfs used in the Monte Carlo simulation

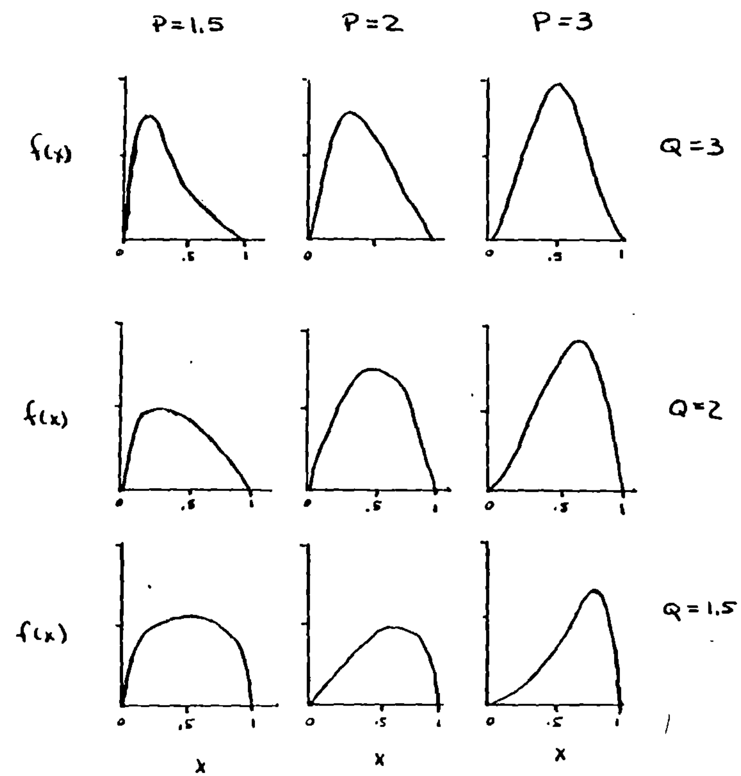


FIGURE 2A Beta densities for various choices of the P and Q parameters

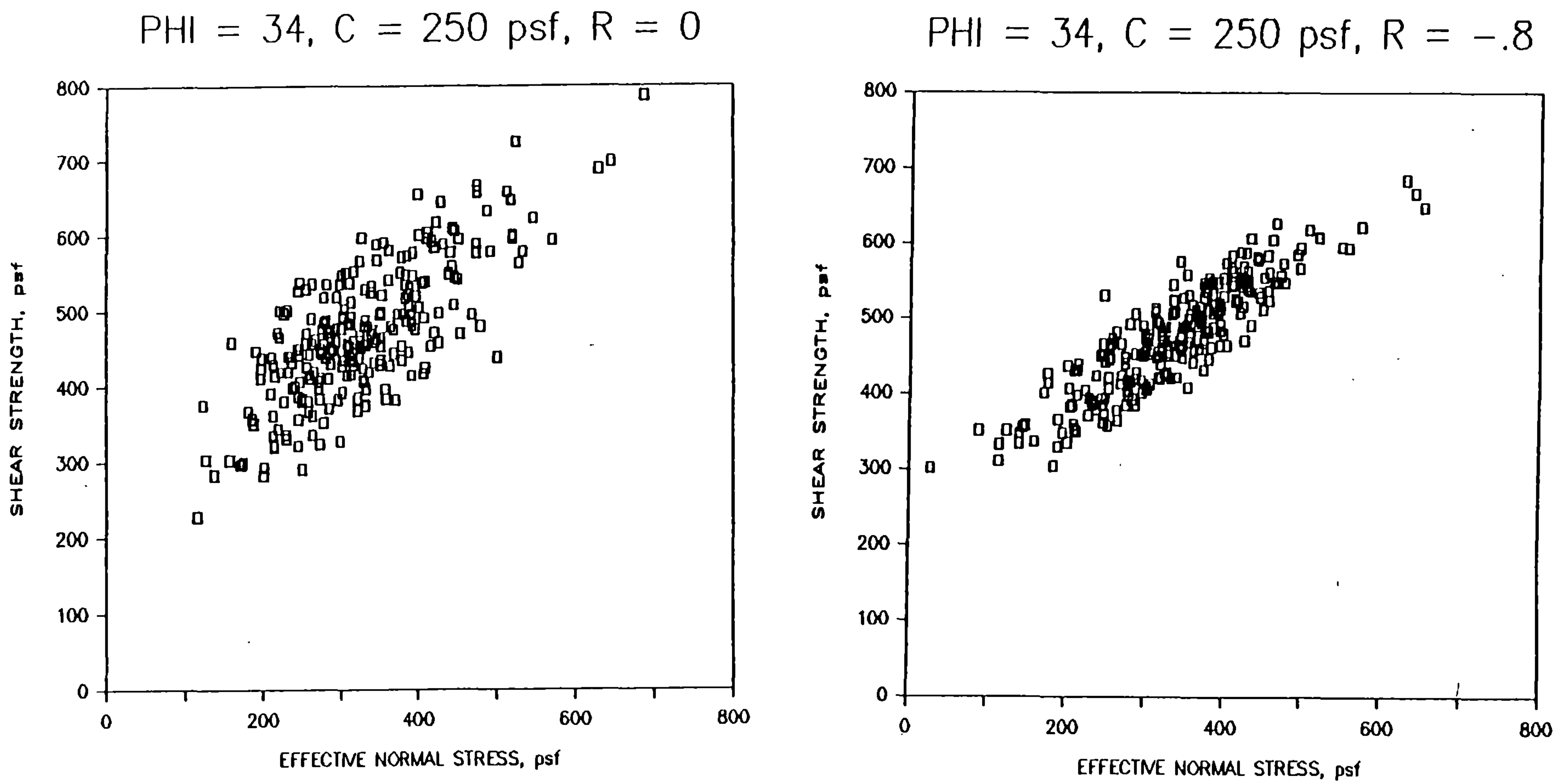

PHI = 34, C = 250 psf, R = 0
SHEAR STRENGTH, psf
EFFECTIVE NORMAL STRESS, psf
0
100
200
300
400
500
600
700
800
PHI = 34, C = 250 psf, R = -.8
SHEAR STRENGTH, psf
EFFECTIVE NORMAL STRESS, psf

FIGURE 3

SENSITIVITY OF THE FACTOR OF SAFETY EQUATION

It is helpful before conducting a probabilistic study of the factor of safety to have a good feeling for which random variables cause the greatest relative change in the factor of safety using the infinite slope equation. Identifying the most important variables guides you in where to spend your time and money collecting information. The steps for evaluating the sensitivity of the factor of safety to each variable have been outlined by Simons, Li and Ward in Mapping of Potential Landslide Areas in Terms of Slope Stability - Draft Copy, 1978:

1) Select a realistic range of values for each input variable.

2) Calculate a base factor of safety value using the mean value for each variable.

3) Vary the value for one input variable at a time over the range of realistic values and compute the factors of safety.

4) Plot the percent change in factor of safety relative to the base value against the percent change in each input variable relative to the mean value.

Figure 4 is an example plot from Simons, Si and Ward. This plot is for a selected set of values. The relative importance of each variable will change depending on the mean values selected. However, in general slope, soil depth, friction angle and ground water ratio are the most important; soil unit weight, moisture content and tree surcharge are the least important. Soil and root cohesion become more important at shallow soil depths.

If the variance of the factor of safety is reduced, the probability of failure that is estimated will change as illustrated in Figure 5. Therefore it is helpful to understand the effect of the variance of each input variable on the variance in the factor of safety [VAR (FS)]. The variance in the factor of safety due to each variable is calculated by:

$$\mathrm{VAR\ (FS)} = \mathrm{Si}^2 * \mathrm{VAR\ (variable\ i)}$$

Si is the sensitivity coefficient for the ith variable and is estimated by:

$$\mathrm{Si} = \Delta \mathrm{FS} \,/\, \Delta \mathrm{Xi}$$

where Δ FS is the change in factor of safety caused by a ΔXi change from the mean of the ith variable. If the variance of each input variable is multiplied by .5, 2 and 3 and the new VAR (FS) calculated, the effect of the variance of each variable on VAR (FS) is better demonstrated. Figure 6 is a plot of the ratio of the variance of the ith variable divided by the initial variance value selected, against VAR (FS) for one set of input values. This figure shows that the variance of slope, soil depth, friction angle and ground water ratio have the greatest effect on VAR (FS). The relative importance of these four variables may change with the mean of the variable and it's initial variance. The effect of tree

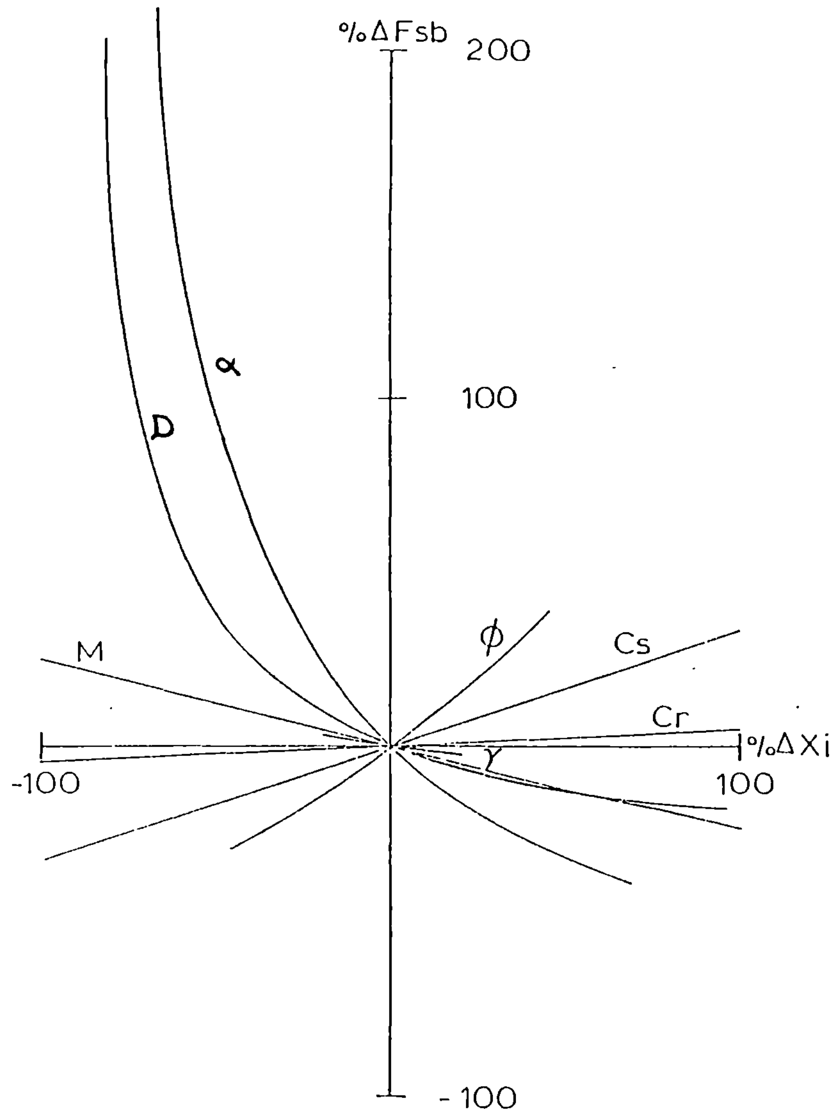


Figure 4. Percent change in FS versus percent change in variable.

from SIMONS, LI AND WARD, 1978

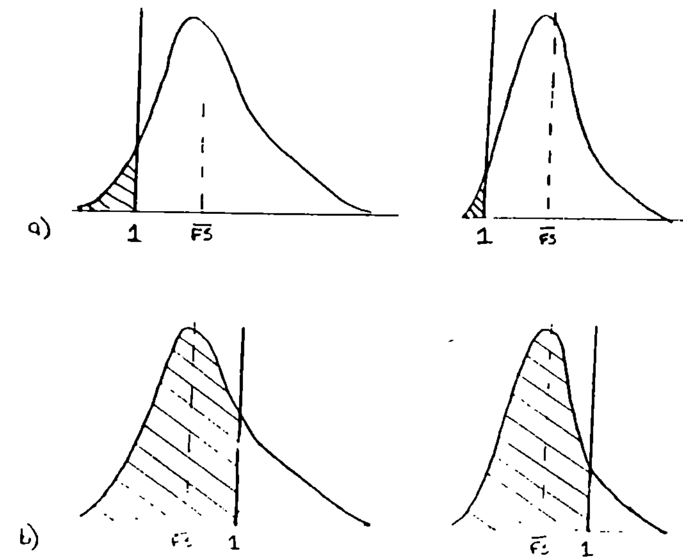


FIGURE 5 a) For $\overline{FS}>1$, the probability of failure decreases as VAR(FS) decreases.

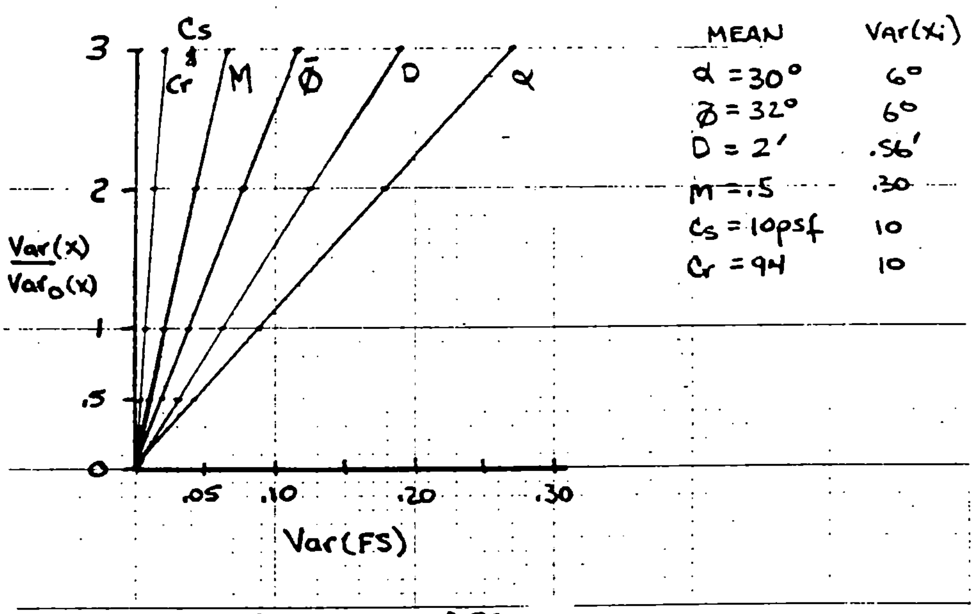
b) For $\overline{FS}<1$, the probability of failure increases as VAR(FS) decreases.

surcharge, soil unit weight and moisture content were too small to plot on the figure.

In summary, for most values of the input variables, changes in the value and variance of slope, soil depth, friction angle and ground water ratio have the greatest relative effect on both the value of the factor of safety and the variance of factor of safety. Which of these are most important should be determined for the range of values which are pertinent to your problem.

FIGURE 6

Var (FS) due to Var (Xi)



$$S_i = \partial FS / \partial x_i = \Delta FS / \Delta x_i$$

$$\therefore \; Var(FS) = S_i^2 * Var(X_i)$$

INTERPRETATION OF THE PROBABILITY OF FAILURE

The probability of failure [P(FS<=1)] should strictly be interpreted as the number of Monte Carlo random realizations of factor of safety (i.e calculated values of factors of safety from simulated data) with values less than or equal to 1 divided by the total number of trials. Since the probability density function (pdf) of each input parameter (except groundwater) represents the areal distribution of that parameter, the probability of failure can be thought of as the expected percent area involved in failure during the time period represented by the groundwater pdf. For a Level II analysis, the probability of failure can be thought of as the expected percent road length involved in failure. Statisticians may argue with these interpretations, but it makes the results meaningful to the manager and useful in cost estimation and decision analysis. If one is quite uncertain about the distributions the variables take on, the probabilties of failure should be thought of as relative when comparing one area to the next.

The groundwater probability density function (pdf) is the pdf of the yearly maximum groundwater ratios (Dw/D) for a number of years of interest (Ty). The probability that the yearly maximum ground water ratio will exceed some threshold value (H') is calculated from a data set (real or modelled) of yearly maximum Dw/D values using Gumbel extreme value statistics. The pdf is estimated by calculating the exceedence probabilities for a series of threshold values. An example calculation of histogram pdfs for 1, 10 and 20 years is given below:

$$P(DW/D > H') = 1 - \exp[-Ty*\exp(-B[H'-\mu])] \qquad (1)$$

where:

P(DW/D > H') = the probability that the yearly maximum ground water ratio will exceed some threshold value (H') in a given number of years (Ty).

$B = SN/sm$ — sm = the standard deviation of the maxima; m = the mean of the maxima

$\mu = m-(MN/B)$ — MN and SN are the mean and the standard deviation of the Gumbel Type I distribution and have been tabulated by Gumbel.

Steps:

1) Obtain or model a data set of the maximum groundwater ratios each year for a period of years. For example, 25 years of record vas the following mean and standard deviation, and frequency distribution:

	1.0
0 of 25	0.8
1 of 25	0.6
3 of 25	0.4
12 of 25	0.2
9 of 25	0.0

m = .2744
sm = .1522
B = 1.09145/.1522 = 7.1693
μ = .2744-(.53186/7.1693)=.2004

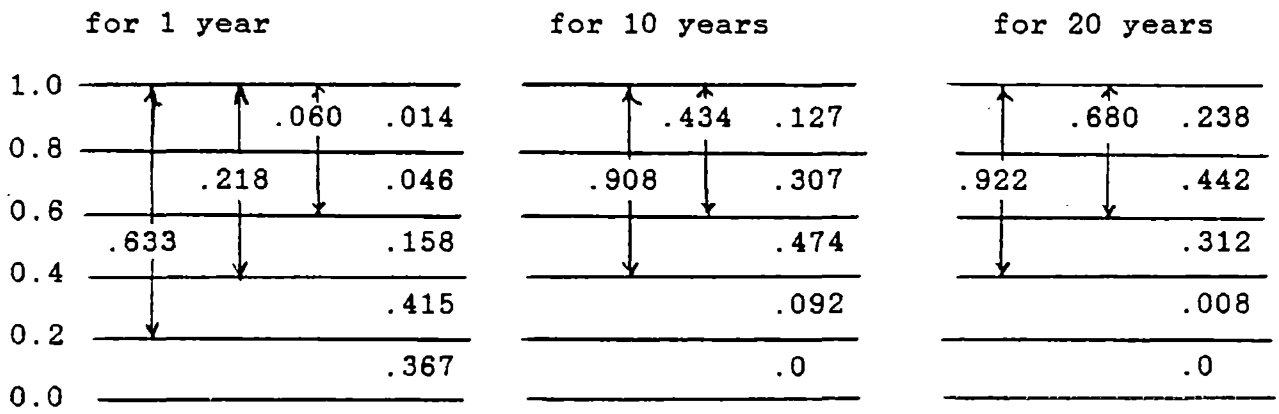
2) Calculate the probabilities of exceeding Dw/D using equation 1.

Dw/D	for 1 year	for 10 years	for 20 years
0.0	1.000	1.000	1.000
0.2	0.633	1.000	1.000
0.4	0.218	0.908	0.992
0.6	0.060	0.434	0.680
0.8	0.014	0.127	0.238
1.0	0.0	0.0	0.0

Note how the probability of exceeding a certain Dw/D value increase as the time under consideration increases.

3) Calculate the probability that the maximum groundwater ratio will fall in each interval during Ty.

P(H'1 < Dw/D < H'2) = P(Dw/D > H'1) - P(Dw/D > H'2)



These figures can be used as histogram distributions for ground water in LISA.

PROBLEM 1
LEVEL 1 STABILITY ANALYSIS

Management has designated 3 cutting areas for analysis. The alternatives for each area are 1) no development, 2) cut 50-percent of the timber, or 3) clearcut the area. These are sensitive areas that will be logged without roading (i.e. helicopter or skyline system).

Use the Level I Stability Analysis monte carlo program (LISA) to estimate the probabilities of slope failure which will be used in a decision analysis in Problem 2.

LEVEL I STABILITY ANALYSIS FOR AREA A

```
OPERATOR     : CJH
DATE / TIME  : 02-23-1987      14:57
MPU   FILE   : CEDAR.MPU
# OF SAMPLES: 1000

Probability of failure      .562
```

INPUT PARAMETERS
===============

```
SITE  FILE   : UNCUT.SIT
     SOIL DEPTH          (ft)   HISTOGRAM.  5 CELLS
                  MIN          MAX     PERCENT
                  .50         2.00        5.00
                 2.00         4.00       10.00
                 4.00         7.00       40.00
                 7.00         9.00       30.00
                 9.00        12.00       15.00
     SLOPE               (%)    TRIANGULAR.
        MIN.:      45.00  MAX.:     75.00  APEX:      65.00
     TREE SURCHARGE      (psf) UNIFORM.
        MIN.:      58.00  MAX.:     14.00
     ROOT COHESION       (psf) NORMAL.
        MEAN:      94.00  S.D.:     10.00

MATERIAL  FILE   : A.MTL
     FRICTION ANGLE     (deg) BETA.
        MIN.:      25.00  MAX.:     30.00     P:      3.00     Q:      2.00
     SOIL COHESION      (psf) NORMAL.
        MEAN:      20.00  S.D.:      3.00
     DRY DENSITY        (pcf) NORMAL.
        MEAN:      90.00  S.D.:      4.00
     MOISTURE CONTENT (%)    NORMAL.
        MEAN:      15.00  S.D.:      5.00
  SPECIFIC GRAVITY OF SOLIDS        2.650
  R (tan PHI. Cs)                    .000

GROUNDWATER FILE   : UNCUT.HYD
     dw/d RATIO                TRIANGULAR.
        MIN.:        .10  MAX.:      1.00  APEX:       .50
```

DESCRIPTIVE STATISTICS
====================

	MIN	MAX	MEAN	S.D.
FACTOR OF SAFETY	.55	5.39	1.06	.38
SOIL DEPTH (ft)	.52	11.96	6.56	2.57
SURFACE SLOPE (%)	46.06	74.71	61.50	6.37
TREE SURCHARGE (psf)	14.02	57.95	36.25	12.69
ROOT COHESION (psf)	63.10	124.90	93.73	10.15
FRICTION ANGLE (deg)			28.00	1.00
SOIL COHESION (psf)			20.00	3.00
DRY DENSITY (pcf)	77.64	101.02	89.84	3.89
MOIST DENSITY (pcf)	83.71	123.96	103.35	6.36
SAT. DENSITY (pcf)	110.74	125.30	118.34	2.43
MOISTURE CONTENT (%)	.30	30.31	15.04	5.12
DW/D RATIO	.11	1.00	.54	.19
SHEAR STRENGTH (psf)	39.43	506.10	230.70	83.69

Probability of failure =   .562

LEVEL I STABILITY ANALYSIS FOR AREA A -- 50% CUT

OPERATOR : CJH
DATE / TIME : 02-23-1987 15:03
MPU FILE : CEDAR.MPU
OF SAMPLES: 1000

Probability of failure .834

INPUT PARAMETERS

SITE FILE : 50CUT.SIT

SOIL DEPTH (ft) HISTOGRAM. 5 CELLS

MIN	MAX	PERCENT
.50	2.00	5.00
2.00	4.00	10.00
4.00	7.00	40.00
7.00	9.00	30.00
9.00	12.00	15.00

SLOPE (%) TRIANGULAR.
MIN.: 45.00 MAX.: 75.00 APEX: 65.00

TREE SURCHARGE (psf) NORMAL.
MEAN: 25.00 S.D.: 7.00

ROOT COHESION (psf) NORMAL.
MEAN: 60.00 S.D.: 5.00

MATERIAL FILE : A.MTL

FRICTION ANGLE (deg) BETA.
MIN.: 25.00 MAX.: 30.00 P: 3.00 Q: 2.00

SOIL COHESION (psf) NORMAL.
MEAN: 20.00 S.D.: 3.00

DRY DENSITY (pcf) NORMAL.
MEAN: 90.00 S.D.: 4.00

MOISTURE CONTENT (%) NORMAL.
MEAN: 15.00 S.D.: 5.00

SPECIFIC GRAVITY OF SOLIDS 2.650

R (tan PHI, Cs) .000

GROUNDWATER FILE : 50CUT.HYD

dw/d RATIO TRIANGULAR.
MIN.: .25 MAX.: 1.00 APEX: .70

DESCRIPTIVE STATISTICS

	MIN	MAX	MEAN	S.D.
FACTOR OF SAFETY	.48	3.21	.87	.29
SOIL DEPTH (ft)	.52	11.99	6.57	2.56
SURFACE SLOPE (%)	46.56	74.55	61.77	6.00
TREE SURCHARGE (psf)	3.52	46.63	25.16	7.07
ROOT COHESION (psf)	44.55	75.45	59.92	5.05
FRICTION ANGLE (deg)			28.00	1.00
SOIL COHESION (psf)			20.00	3.00
DRY DENSITY (pcf)	78.30	102.36	90.05	3.86
MOIST DENSITY (pcf)	84.14	123.71	103.73	6.13
SAT. DENSITY (pcf)	111.15	126.13	118.47	2.41
MOISTURE CONTENT (%)	.60	30.45	15.19	4.71
DW/D RATIO	.25	.99	.66	.15
SHEAR STRENGTH (psf)	39.21	481.18	212.80	75.52

Probability of failure = .834

LEVEL I STABILITY ANALYSIS FOR AREA A -- CLEARCUT

OPERATOR : CJH
DATE / TIME : 02-23-1987 15:08
MPU FILE : CEDAR.MPU
OF SAMPLES: 1000

Probability of failure .978

INPUT PARAMETERS
===============

SITE FILE : CLEARCUT.SIT

SOIL DEPTH (ft) HISTOGRAM. 5 CELLS

MIN	MAX	PERCENT
.50	2.00	5.00
2.00	4.00	10.00
4.00	7.00	40.00
7.00	9.00	30.00
9.00	12.00	15.00

SLOPE (%) TRIANGULAR.
MIN.: 45.00 MAX.: 75.00 APEX: 65.00

TREE SURCHARGE (psf)
.00

ROOT COHESION (psf) NORMAL.
MEAN: 10.00 S.D.: 1.00

MATERIAL FILE : A.MTL

FRICTION ANGLE (deg) BETA.
MIN.: 25.00 MAX.: 30.00 P: 3.00 Q: 2.00

SOIL COHESION (psf) NORMAL.
MEAN: 20.00 S.D.: 3.00

DRY DENSITY (pcf) NORMAL.
MEAN: 90.00 S.D.: 4.00

MOISTURE CONTENT (%) NORMAL.
MEAN: 15.00 S.D.: 5.00

SPECIFIC GRAVITY OF SOLIDS 2.650
R (tan PHI, Cs) .000

GROUNDWATER FILE : CLEARCUT.HYD

dw/d RATIO TRIANGULAR.
MIN.: .50 MAX.: 1.00 APEX: .95

DESCRIPTIVE STATISTICS
====================

	MIN	MAX	MEAN	S.D.
FACTOR OF SAFETY	.40	1.54	.61	.13
SOIL DEPTH (ft)	.53	12.00	6.49	2.56
SURFACE SLOPE (%)	45.42	74.77	61.70	6.21
TREE SURCHARGE (psf)	.00	.00	.00	.00
ROOT COHESION (psf)	6.91	13.06	9.94	1.00
FRICTION ANGLE (deg)			28.00	1.00
SOIL COHESION (psf)			20.00	3.00
DRY DENSITY (pcf)	78.38	102.36	90.04	4.01
MOIST DENSITY (pcf)	86.31	125.34	103.72	6.27
SAT. DENSITY (pcf)	111.20	126.13	118.47	2.50
MOISTURE CONTENT (%)	.12	30.45	15.20	4.87
DW/D RATIO	.51	.99	.82	.11
SHEAR STRENGTH (psf)	32.29	406.85	182.54	67.84

Probability of failure = .978

LEVEL I STABILITY ANALYSIS FOR AREA B -- UNCUT

OPERATOR : CJH
DATE / TIME : 02-23-1987 15:20
MPU FILE : DOUG.MPU
OF SAMPLES: 1000

Probability of failure .032

INPUT PARAMETERS

SITE FILE : UNCUT.SIT
SOIL DEPTH (ft) TRIANGULAR.
MIN.: .50 MAX.: 5.00 APEX: 2.50
SLOPE (%) HISTOGRAM. 3 CELLS

MIN	MAX	PERCENT
75.00	90.00	60.00
90.00	100.00	30.00
100.00	110.00	10.00

TREE SURCHARGE (psf) UNIFORM.
MIN.: 35.00 MAX.: 85.00
ROOT COHESION (psf) UNIFORM.
MIN.: 100.00 MAX.: 150.00

MATERIAL FILE : B.MTL
FRICTION ANGLE (deg) TRIANGULAR.
MIN.: 30.00 MAX.: 37.00 APEX: 34.00
SOIL COHESION (psf) TRIANGULAR.
MIN.: 5.00 MAX.: 15.00 APEX: 10.00
DRY DENSITY (pcf) NORMAL.
MEAN: 100.00 S.D.: 3.00
MOISTURE CONTENT (%) NORMAL.
MEAN: 15.00 S.D.: 5.00
SPECIFIC GRAVITY OF SOLIDS 2.640
R (tan PHI, Cs) .000

GROUNDWATER FILE : UNCUT.HYD
dw/d RATIO TRIANGULAR.
MIN.: .10 MAX.: 1.00 APEX: .20

DESCRIPTIVE STATISTICS

	MIN	MAX	MEAN	S.D.
FACTOR OF SAFETY	.80	3.13	1.43	.33
SOIL DEPTH (ft)	.63	4.89	2.65	.92
SURFACE SLOPE (%)	75.01	109.98	88.39	8.84
TREE SURCHARGE (psf)	35.06	84.99	59.88	14.87
ROOT COHESION (psf)	100.03	149.98	125.42	14.39
FRICTION ANGLE (deg)			33.67	1.43
SOIL COHESION (psf)			10.00	2.04
DRY DENSITY (pcf)	90.73	109.27	99.95	3.01
MOIST DENSITY (pcf)	95.94	129.09	114.91	5.73
SAT. DENSITY (pcf)	118.76	130.28	124.49	1.87
MOISTURE CONTENT (%)	1.48	25.43	14.96	4.49
DW/D RATIO	.10	.99	.43	.20
SHEAR STRENGTH (psf)	47.64	247.04	124.10	36.65

Probability of failure = .032

LEVEL I STABILITY ANALYSIS FOR AREA B -- 50% CUT

OPERATOR : CJH
DATE / TIME : 02-23-1987 15:25
MPU FILE : DOUG.MPU
OF SAMPLES: 1000

Probability of failure .477

INPUT PARAMETERS

SITE FILE : 50CUT.SIT
SOIL DEPTH (ft) TRIANGULAR.
MIN.: .50 MAX.: 5.00 APEX: 2.50
SLOPE (%) HISTOGRAM. 3 CELLS

MIN	MAX	PERCENT
75.00	90.00	60.00
90.00	100.00	30.00
100.00	110.00	10.00

TREE SURCHARGE (psf) UNIFORM.
MIN.: 10.00 MAX.: 40.00
ROOT COHESION (psf) UNIFORM.
MIN.: 50.00 MAX.: 75.00

MATERIAL FILE : B.MTL
FRICTION ANGLE (deg) TRIANGULAR.
MIN.: 30.00 MAX.: 37.00 APEX: 34.00
SOIL COHESION (psf) TRIANGULAR.
MIN.: 5.00 MAX.: 15.00 APEX: 10.00
DRY DENSITY (pcf) NORMAL.
MEAN: 100.00 S.D.: 3.00
MOISTURE CONTENT (%) NORMAL.
MEAN: 15.00 S.D.: 5.00
SPECIFIC GRAVITY OF SOLIDS 2.640
R (tan PHI, Cs) .000

GROUNDWATER FILE : 50CUT.HYD
dw/d RATIO TRIANGULAR.
MIN.: .10 MAX.: 1.00 APEX: .40

DESCRIPTIVE STATISTICS

	MIN	MAX	MEAN	S.D.
FACTOR OF SAFETY	.66	2.20	1.05	.22
SOIL DEPTH (ft)	.67	4.87	2.71	.90
SURFACE SLOPE (%)	75.01	109.87	88.59	8.70
TREE SURCHARGE (psf)	10.05	39.97	24.97	8.57
ROOT COHESION (psf)	50.10	75.00	62.61	7.10
FRICTION ANGLE (deg)			33.67	1.43
SOIL COHESION (psf)			10.00	2.04
DRY DENSITY (pcf)	90.73	109.27	100.14	3.11
MOIST DENSITY (pcf)	95.78	129.13	115.32	5.93
SAT. DENSITY (pcf)	118.76	130.28	124.61	1.92
MOISTURE CONTENT (%)	[illegible].11	25.99	15.16	4.75
DW/D RATIO	.10	.99	.49	.19
SHEAR STRENGTH (psf)	30.81	224.97	109.62	33.84

Probability of failure = .477

LEVEL I STABILITY ANALYSIS OF AREA B -- CLEARCUT

OPERATOR : CJH
DATE / TIME : 02-23-1987 15:30
MPU FILE : DOUG.MPU
OF SAMPLES: 1000

Probability of failure .990

INPUT PARAMETERS
================

SITE FILE : CLEAR.SIT
SOIL DEPTH (ft) TRIANGULAR.
MIN.: .50 MAX.: 5.00 APEX: 2.50
SLOPE (%) HISTOGRAM: 3 CELLS

MIN	MAX	PERCENT
75.00	90.00	60.00
90.00	100.00	30.00
100.00	110.00	10.00

TREE SURCHARGE (psf)
.00
ROOT COHESION (psf) UNIFORM.
MIN.: .00 MAX.: 20.00

MATERIAL FILE : B.MTL
FRICTION ANGLE (deg) TRIANGULAR.
MIN.: 30.00 MAX.: 37.00 APEX: 34.00
SOIL COHESION (psf) TRIANGULAR.
MIN.: 5.00 MAX.: 15.00 APEX: 10.00
DRY DENSITY (pcf) NORMAL.
MEAN: 100.00 S.D.: 3.00
MOISTURE CONTENT (%) NORMAL.
MEAN: 15.00 S.D.: 5.00
SPECIFIC GRAVITY OF SOLIDS 2.640
R (tan PHI, Cs) .000

GROUNDWATER FILE : CLEAR.HYD
dw/d RATIO TRIANGULAR.
MIN.: .25 MAX.: 1.00 APEX: .60

DESCRIPTIVE STATISTICS
======================

	MIN	MAX	MEAN	S.D.
FACTOR OF SAFETY	.40	1.24	.67	.11
SOIL DEPTH (ft)	.72	4.79	2.68	.91
SURFACE SLOPE (%)	75.00	109.99	88.50	8.76
TREE SURCHARGE (psf)	.00	.00	.00	.00
ROOT COHESION (psf)	.01	19.99	10.00	5.74
FRICTION ANGLE (deg)			33.67	1.43
SOIL COHESION (psf)			10.00	2.04
DRY DENSITY (pcf)	91.45	109.02	100.13	2.97
MOIST DENSITY (pcf)	99.79	129.32	115.05	5.83
SAT. DENSITY (pcf)	119.21	130.12	124.60	1.84
MOISTURE CONTENT (%)	.73	25.79	14.90	4.73
DW/D RATIO	.26	.99	.61	.15
SHEAR STRENGTH (psf)	24.66	188.03	93.47	31.43

Probability of failure = .990

LEVEL I STABILITY ANALYSIS FOR AREA C -- UNCUT

OPERATOR : CJH
DATE / TIME : 02-23-1987 15:39
MPU FILE : WHITE.MPU
OF SAMPLES: 1000

Probability of failure .008

INPUT PARAMETERS

```
SITE FILE : UNCUT.SIT
    SOIL DEPTH          (ft)  TRIANGULAR.
       MIN.:      2.00  MAX.:     15.00  APEX:     10.00
    SLOPE               (%)   HISTOGRAM.  3 CELLS
                 MIN         MAX      PERCENT
               20.00       30.00      50.00
               30.00       40.00      30.00
               40.00       50.00      20.00
    TREE SURCHARGE      (psf) UNIFORM.
       MIN.:     10.00  MAX.:     50.00
    ROOT COHESION       (psf) UNIFORM.
       MIN.:     40.00  MAX.:    120.00

MATERIAL FILE : C.MTL
    FRICTION ANGLE      (deg) BETA.
       MIN.:     28.00  MAX.:     33.00      P:     3.00    Q:     2.00
    SOIL COHESION       (psf) NORMAL.
       MEAN:     50.00  S.D.:      2.00
    DRY DENSITY         (pcf) NORMAL.
       MEAN:     95.00  S.D.:      4.00
    MOISTURE CONTENT (%)      NORMAL.
       MEAN:     18.00  S.D.:      5.00
  SPECIFIC GRAVITY OF SOLIDS      2.640
  R (tan PHI, Cs)                 -.800

GROUNDWATER FILE : UNCUT.HYD
    dw/d RATIO                TRIANGULAR.
       MIN.:       .20  MAX.:      1.00  APEX:       .40
```

DESCRIPTIVE STATISTICS

	MIN	MAX	MEAN	S.D.
FACTOR OF SAFETY	.85	4.07	1.93	.53
SOIL DEPTH (ft)	2.22	14.51	9.08	2.65
SURFACE SLOPE (%)	20.00	49.94	32.17	8.23
TREE SURCHARGE (psf)	10.01	49.97	30.35	11.54
ROOT COHESION (psf)	40.19	119.97	79.97	23.36
FRICTION ANGLE (deg)			31.00	1.00
SOIL COHESION (psf)			50.00	2.00
DRY DENSITY (pcf)	83.23	107.36	95.01	4.09
MOIST DENSITY (pcf)	91.37	126.40	111.84	6.42
SAT. DENSITY (pcf)	114.10	129.09	121.42	2.54
MOISTURE CONTENT (%)	2.55	30.08	17.73	4.74
DW/D RATIO	.20	.97	.53	.17
SHEAR STRENGTH (psf)	156.44	828.12	480.67	133.69

Probability of failure = .008

LEVEL I STABILITY ANALYSIS FOR AREA C — 50% CUT

OPERATOR : CJH
DATE / TIME : 02-23-1987 15:44
MPU FILE : WHITE.MPU
OF SAMPLES: 1000

Probability of failure .041

INPUT PARAMETERS

SITE FILE : 50CUT.SIT
SOIL DEPTH (ft) TRIANGULAR.
MIN.: 2.00 MAX.: 15.00 APEX: 10.00
SLOPE (%) HISTOGRAM. 3 CELLS

MIN	MAX	PERCENT
20.00	30.00	50.00
30.00	40.00	30.00
40.00	50.00	20.00

TREE SURCHARGE (psf) UNIFORM.
MIN.: 5.00 MAX.: 25.00
ROOT COHESION (psf) UNIFORM.
MIN.: 20.00 MAX.: 60.00

MATERIAL FILE : C.MTL
FRICTION ANGLE (deg) BETA.
MIN.: 28.00 MAX.: 33.00 P: 3.00 Q: 2.00
SOIL COHESION (psf) NORMAL.
MEAN: 50.00 S.D.: 2.00
DRY DENSITY (pcf) NORMAL.
MEAN: 95.00 S.D.: 4.00
MOISTURE CONTENT (%) NORMAL.
MEAN: 18.00 S.D.: 5.00
SPECIFIC GRAVITY OF SOLIDS 2.640
R (tan PHI, Cs) -.800

GROUNDWATER FILE : 50CUT.HYD
dw/d RATIO TRIANGULAR.
MIN.: .20 MAX.: 1.00 APEX: .60

DESCRIPTIVE STATISTICS

	MIN	MAX	MEAN	S.D.
FACTOR OF SAFETY	.82	3.43	1.71	.48
SOIL DEPTH (ft)	2.25	14.81	8.91	2.69
SURFACE SLOPE (%)	20.00	49.83	32.02	8.29
TREE SURCHARGE (psf)	5.00	24.99	15.29	5.64
ROOT COHESION (psf)	20.03	59.94	39.67	12.02
FRICTION ANGLE (deg)			31.00	1.00
SOIL COHESION (psf)			50.00	2.00
DRY DENSITY (pcf)	82.64	107.29	94.89	3.83
MOIST DENSITY (pcf)	90.73	126.06	111.87	6.35
SAT. DENSITY (pcf)	113.74	129.05	121.35	2.38
MOISTURE CONTENT (%)	2.55	31.19	17.89	4.88
DW/D RATIO	.22	.98	.61	.17
SHEAR STRENGTH (psf)	137.22	834.46	443.86	128.25

Probability of failure = .041

LEVEL I STABILITY ANALYSIS FOR AREA C -- CLEARCUT

```
OPERATOR     : CJH
DATE / TIME  : 02-23-1987     15:49
MPU   FILE   : WHITE.MPU
# OF SAMPLES: 1000

Probability of failure     .122
```

INPUT PARAMETERS

```
SITE  FILE  : CLEARCUT.SIT
     SOIL DEPTH        (ft)  TRIANGULAR.
        MIN.:      2.00  MAX.:     15.00  APEX:     10.00
     SLOPE             (%)   HISTOGRAM.  3 CELLS
               MIN    -    MAX    PERCENT
             20.00      30.00     50.00
             30.00      40.00     30.00
             40.00      50.00     20.00
     TREE SURCHARGE    (psf)
           .00
     ROOT COHESION     (psf) UNIFORM.
        MIN.:       .00  MAX.:     10.00

MATERIAL  FILE  : C.MTL
     FRICTION ANGLE    (deg) BETA.
        MIN.:     28.00  MAX.:     33.00     P:      3.00     Q:      2.00
     SOIL COHESION     (psf) NORMAL.
        MEAN:     50.00  S.D.:      2.00
     DRY DENSITY       (pcf) NORMAL.
        MEAN:     95.00  S.D.:      4.00
     MOISTURE CONTENT (%)    NORMAL.
        MEAN:     18.00  S.D.:      5.00
  SPECIFIC GRAVITY OF SOLIDS       2.640
  R (tan PHI, Cs)                  -.800

GROUNDWATER FILE   : CLEARCUT.HYD
     dw/d RATIO                TRIANGULAR.
        MIN.:       .30  MAX.:      1.00  APEX:       .80
```

DESCRIPTIVE STATISTICS

	MIN	MAX	MEAN	S.D.
FACTOR OF SAFETY	.72	2.95	1.49	.41
SOIL DEPTH (ft)	2.27	14.79	8.97	2.63
SURFACE SLOPE (%)	20.00	49.96	31.92	8.27
TREE SURCHARGE (psf)	.00	.00	.00	.00
ROOT COHESION (psf)	.01	9.98	4.96	2.88
FRICTION ANGLE (deg)			31.00	1.00
SOIL COHESION (psf)			50.00	2.00
DRY DENSITY (pcf)	82.64	105.41	95.03	3.92
MOIST DENSITY (pcf)	91.47	127.38	111.89	6.24
SAT. DENSITY (pcf)	113.74	127.88	121.43	2.43
MOISTURE CONTENT (%)	2.55	32.94	17.76	4.77
DW/D RATIO	.31	.99	.70	.15
SHEAR STRENGTH (psf)	135.24	745.53	414.68	116.68

Probability of failure = .122

DECISION ANALYSIS AND DECISION TREES

DEFINITION:

A **DECISION ALTERNATIVE** IS AN OPTION OR CHOICE AVAILABLE TO A DECISION MAKER. USUALLY, THERE ARE SEVERAL SUCH OPTIONS AVAILABLE, AND EACH ONE MUST HAVE AT LEAST TWO POSSIBLE OUTCOMES (SUCH AS SUCCESS OR FAILURE).

AN **OUTCOME** IS AN EVENT OR STATE OF NATURE THAT COULD OCCUR IF A GIVEN ALTERNATIVE IS SELECTED. EACH OUTCOME WILL HAVE SOME PROBABILITY VALUE ASSOCIATED WITH IT.

THERE ARE SEVERAL WAYS TO EVALUATE THE RISKS ASSOCIATED WITH VARIOUS DECISION ALTERNATIVES. TWO COMMONLY USED RISK INDICES ARE:

1. RISK RATIO, OR RELATIVE RISK INDEX, DEFINED AS:

$$R = \frac{\text{(COST OF A LOSS) x (PROB. OF A LOSS OCCURRING)}}{\text{(BENEFIT OF A GAIN) x (PROB. OF A GAIN OCCURRING)}}$$

   THIS IS EQUIVALENT TO THE ANTICIPATED WORTH (COST) OF A LOSS DIVIDED BY THE ANTICIPATED WORTH (BENEFIT) OF A GAIN. R IS A UNITLESS, RELATIVE MEASURE OF RISK. IF R IS CALCULATED FOR TWO DIFFERENT DECISION ALTERNATIVES, THEN LOGICALLY THE ONE WITH THE **LOWER R VALUE** SHOULD BE SELECTED.

2. EXPECTED MONETARY VALUE (**EMV**)

   EMV OF AN OUTCOME - THE PRODUCT OBTAINED BY MULTIPLYING P[OUTCOME OCCURS] BY THE CONDITIONAL VALUE (OR WORTH) RECEIVED IF THE OUTCOME OCCURS.

   EMV OF A DECISION ALTERNATIVE - THE SUM OF THE EMV'S OF ALL POSSIBLE OUTCOMES THAT COULD OCCUR IF THE PARTICULAR DECISION ALTERNATIVE IS SELECTED.

   A NEGATIVE EMV IMPLIES AN EXPECTED NET LOSS, WHEREAS A POSITIVE EMV IMPLIES AN EXPECTED NET GAIN.

   EMV IS INTERPRETED AS THE AVERAGE MONETARY RESULT PER DECISION THAT WOULD OCCUR IF THAT SAME ALTERNATIVE WERE SELECTED OVER A SERIES OF REPEATED TRIALS.

   A DECISION MAKER SHOULD SELECT CONSISTENTLY THE DECISION ALTERNATIVES WITH THE **HIGHEST EMV** TO MAXIMIZE GAIN OVER THE LONG TERM.

DECISION TREE -

A PICTORIAL REPRESENTATION OF A SEQUENCE OF DECISION ALTERNATIVES AND POSSIBLE OUTCOMES.

THERE ARE TWO TYPES OF NODES IN A DECISION TREE:

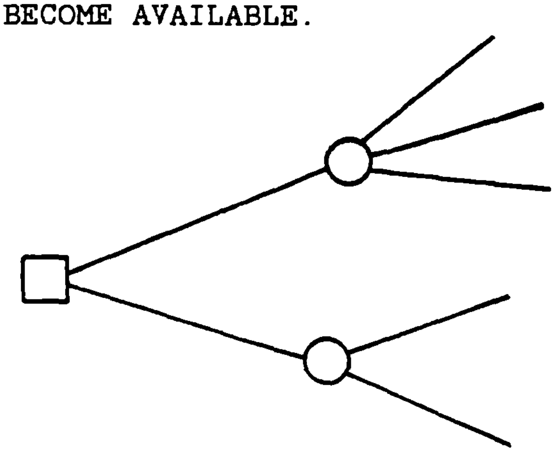
1. DECISION NODE, REPRESENTED BY A SQUARE
2. PROBABILITY NODE, REPRESENTED BY A CIRCLE

   (ALSO KNOWN AS A CHANCE NODE)

"THE DECISION TREE CAN CLARIFY FOR MANAGEMENT, AS NO OTHER ANALYTICAL TOOL THAT I KNOW OF, THE CHOICES, RISKS, OBJECTIVES, MONETARY GAINS, AND INFORMATION NEEDS INVOLVED IN AN INVESTMENT PROBLEM." --
J. MAGEE (HARVARD BUSINESS REVIEW, V. 42, 1964)

IMPORTANT FEATURES OF DECISION TREES:

1. ANY DECISION PROBLEM, EVEN VERY COMPLICATED ONES, CAN BE ANALYSED.
2. ALL POSSIBLE DECISION ALTERNATIVES AND CONTINGENCIES ARE DEFINED PRIOR TO ANY ACTION AND ARE ANALYSED IN A CONSISTENT, RATIONAL MANNER THAT IS EASILY DOCUMENTED.
3. THIS TYPE OF ANALYSIS PROVIDES AN EXCELLENT MECHANISM FOR CONSISTENT, RATIONAL ACTION IN ACHIEVING A GOAL OVER A SERIES OF DECISIONS.
4. A DECISION TREE SERVES AS A "PROGRESS MAP" TO FOLLOW THE SEQUENCE OF EVENTS IN A PROJECT AND TO RE-EVALUATE REMAINING ALTERNATIVES AS NEW CONDITIONS AND INFORMATION BECOME AVAILABLE.



PROBLEM 2
DECISION TREE ANALYSIS USING
LEVEL 1 STABILITY ANALYSIS

Using the following cost/benefit data and the probabilities of failure estimated in Problem 1, construct decision trees and perform the analysis to identify the prefered alternative (alternative with the highest EMV). Note that both high and low costs of failure are provided. How does the cost of failure affect your decision? Compare the EMVs of the 3 areas.

AREA A

		UNCUT	50% CUT	CLEARCUT
TIMBER VALUE		$ 0	$ 720,000	$ 1,440,000
DEVELOPEMENT COST		0	300,000	500,000
COST OF FAILURE	HIGH	720,000	801,000	1,080,000
	LOW	144,000	9,000	288,000

AREA B

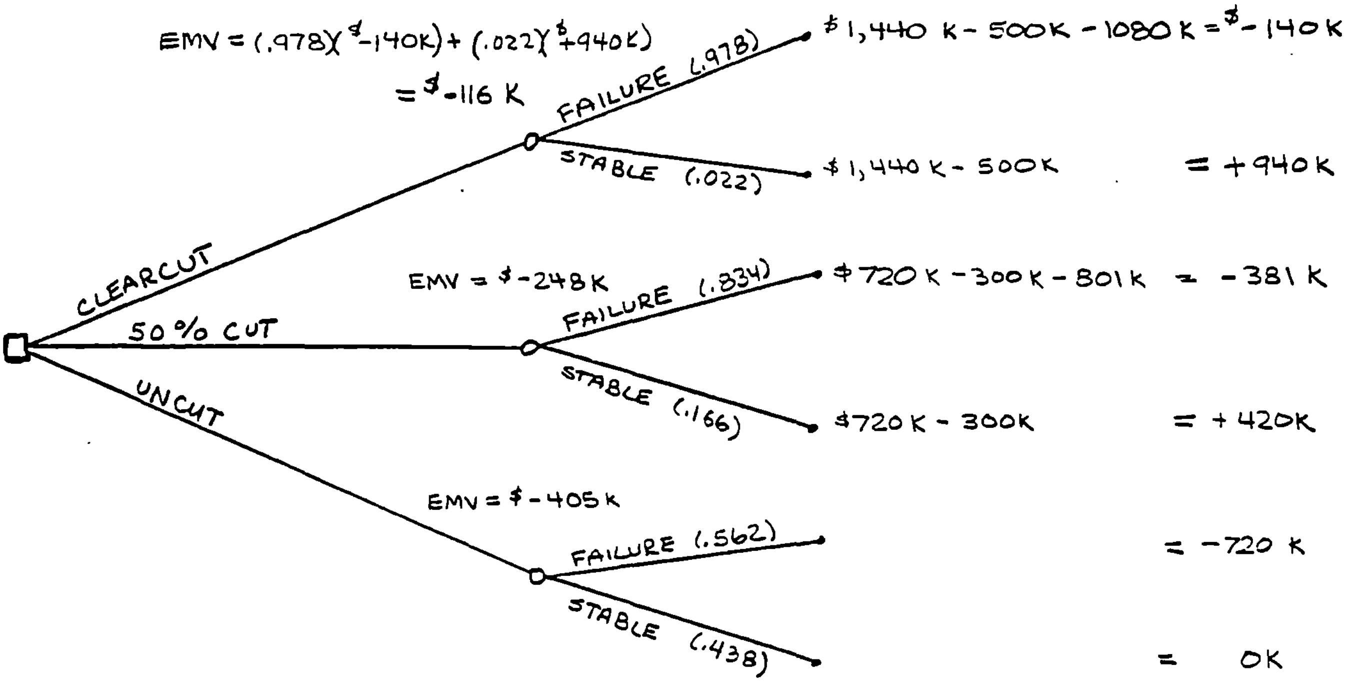
		UNCUT	50% CUT	CLEARCUT
TIMBER VALUE		$ 0	$ 600,000	$ 1,200,000
DEVELOPEMENT COST		0	250,000	450,000
COST OF FAILURE	HIGH	600,000	668,000	900,000
	LOW	120,000	8,000	240,000

AREA C

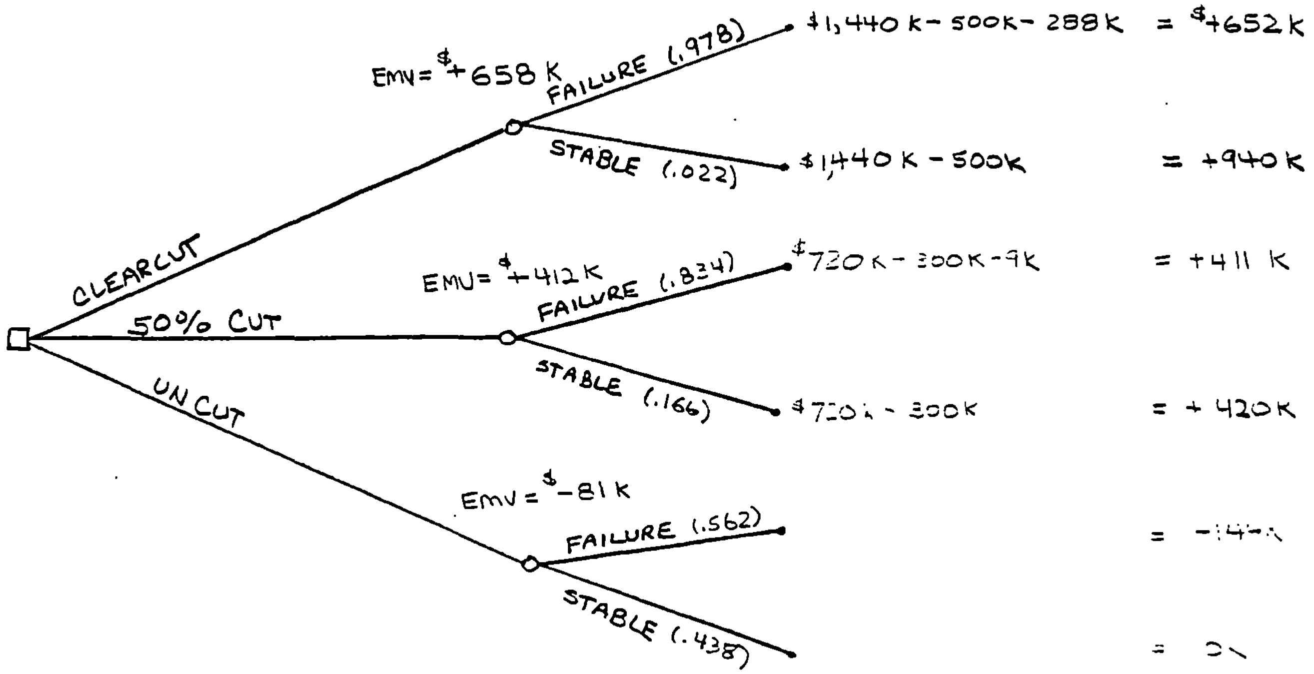
		UNCUT	50% CUT	CLEARCUT
TIMBER VALUE		$ 0	$ 240,000	$ 480,000
DEVELOPEMENT COST		0	130,000	250,000
COST OF FAILURE	HIGH	336,000	338,000	408,000
	LOW	144,000	122,000	192,000

AREA A

HIGH COST OF FAILURE

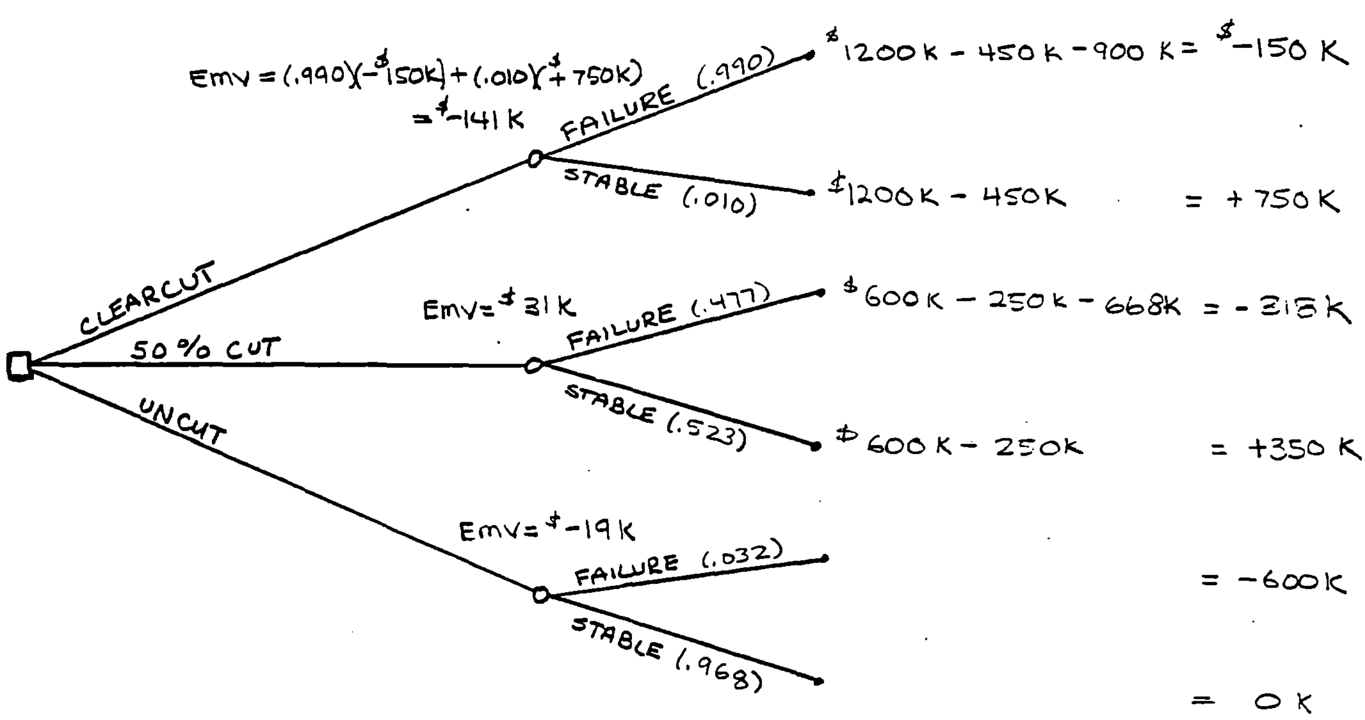


LOW COST OF FAILURE

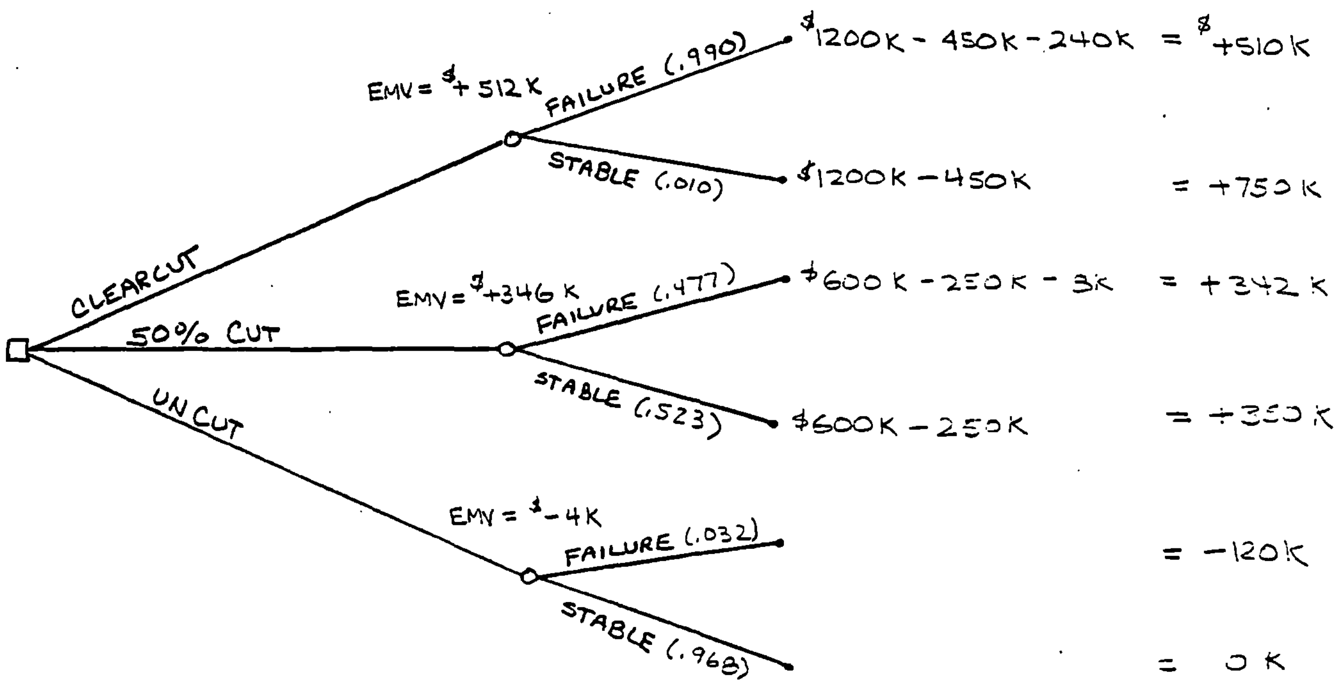


AREA B

High Cost of Failure



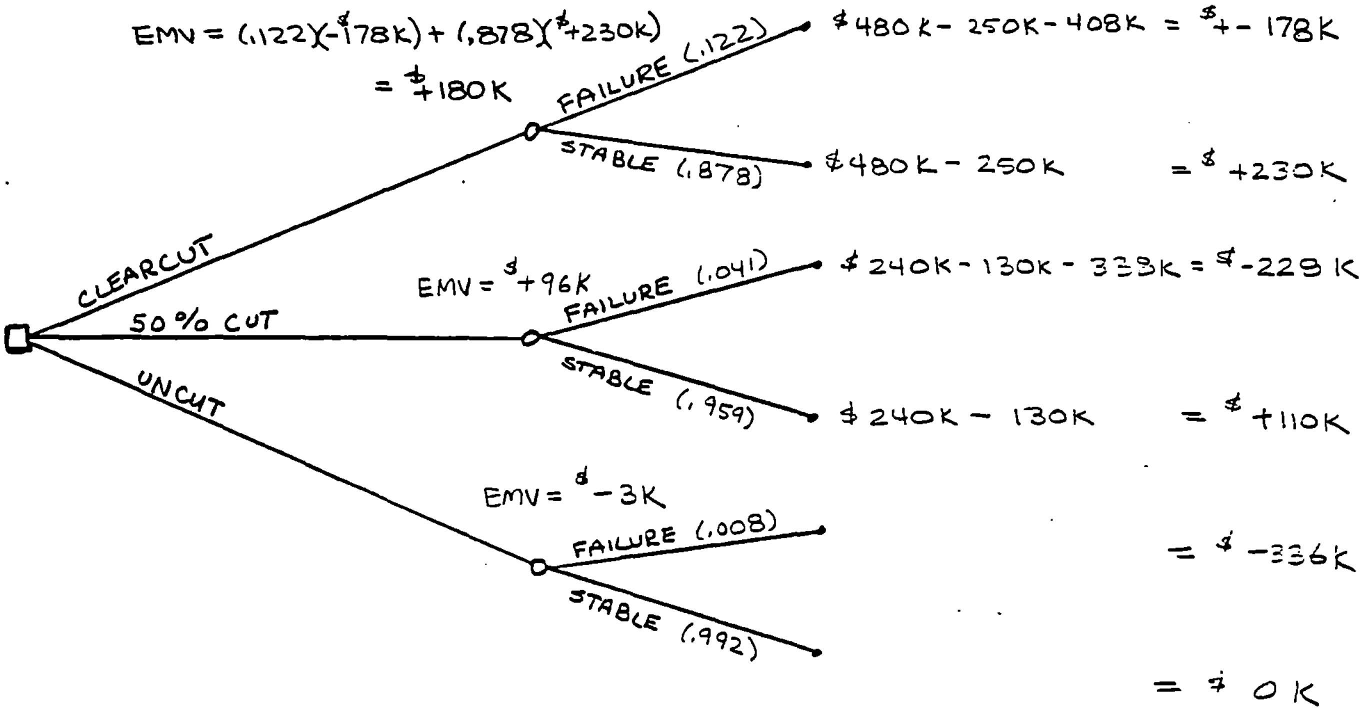
Low Cost of Failure



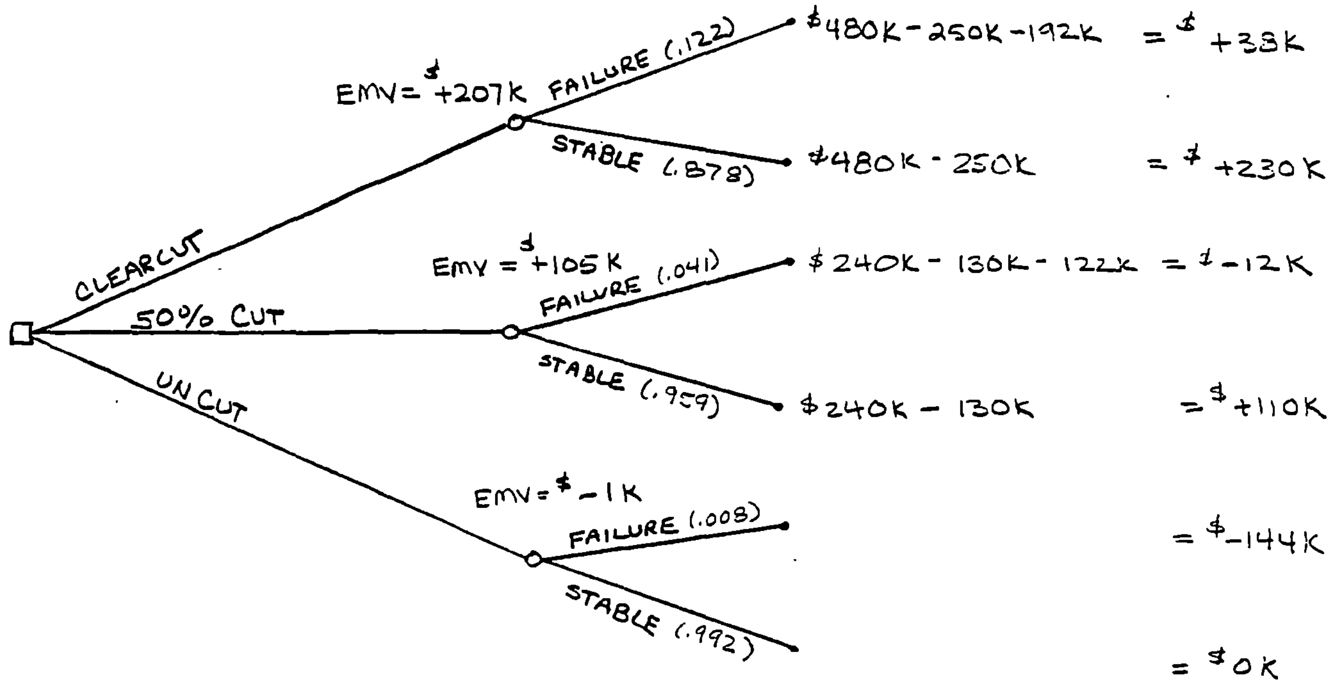
AREA C

HIGH COST OF FAILURE

BENEFIT/COST



LOW COST OF FAILURE



SUMMARY OF RESULTS

EMV
(in thousands of dollars)

	HIGH COST OF FAILURE			LOW COST OF FAILURE		
	CLEARCUT	50 % CUT	UNCUT	CLEARCUT	50 % CUT	UNCUT
AREA A	-116	-248	-405	+658	+412	-81
AREA B	-141	+31	-19	+512	+346	-4
AREA C	+180	+96	-3	+207	+105	-1

APPENDIX
COST INFORMATION

AREA A

TIMBER VALUE: High value timber, such as Cedar.

Clearcut - 40 MBF/acre * 40 acre * $900/MBF = $1,440,000
50 % cut - .5 * $1,440,000 = $ 720,000

DEVELOPEMENT COST: Something less than one half the timber value.

COST OF FAILURE : Because roads are not involved, the cost of failure results from damage to the down slope resources such as visual damage, increased regeneration time, sedimentation, and fisheries damage. The R-6 Geotechnical Drilling Study shows these costs as $10,000 to infinite (p.8). For this problem we have shown high and low cost that are relative to timber values. For 50 % cut, the cost of failure is offset by proceeds from a salvage sale.

Clearcut - High: 0.75 * $1,440,000 = $1,080,000
Low : 0.20 * $1,440,000 = 288,000

50 % Cut - Salvage value Dev. cost
High: $1,080,000 + .35 * $1,440,000 - .75 * $300,000 = -801,000
Low : $ 720,000 + .35 * $1,440,000 - .75 * $300,000 = -9,000

Uncut - High: 0.50 * $1,440,000 = $ 720,000
Low : 0.10 * $1,440,000 = 144,000

AREA B

TIMBER VALUE: Moderate value timber, such as Douglas Fir.

Clearcut - 50 MBF/acre * 40 acre * $600/MBF = $1,200,000
50 % cut - .5 * $1,200,000 = $ 600,000

DEVELOPEMENT COST: Something less than one half the timber value.

COST OF FAILURE :

Clearcut - High: 0.75 * $1,200,000 = $900,000
Low : 0.20 * $1,200,000 = 240,000

50 % Cut - Salvage value Dev. cost
High: $900,000 + .35 * $1,200,000 - .75 * $250,000 = $-668,000
Low : $240,000 + .35 * $1,200,000 - .75 * $250,000 = -8,000

Uncut - High: 0.50 * $1,200,000 = $ 600,000
Low : 0.10 * $1,200,000 = 120,000

AREA C

TIMBER VALUE: Low value timber, such as White Fir.

```
    Clearcut - 40 MBF/acre * 40 acre * $300/MBF = $480,000
    50 % cut - .5 * $480,000                    = $240,000
```

DEVELOPEMENT COST: Something less than one half the timber value.

COST OF FAILURE : This area has a higher cost of failure because it is a visually sensitive site, such as visible from a National Park.

```
Clearcut - High: 0.85 * $480,000 = $408,000
           Low : 0.40 * $480,000 =  192,000

50 % Cut -                Salvage value         Dev. cost
    High:  $408,000 + .35 * $480,000 - .75 * $130,000 = $-338,000
    Low :  $192,000 + .35 * $480,000 - .75 * $130,000 =  -122,000

Uncut    - High: 0.70 * $480,000 = $ 336,000
           Low : 0.30 * $480,000 =   144,000
```

PROBLEM 3
DECISION ANALYSIS USING
LEVEL 1 STABILITY ANALYSIS AND CONDITIONAL PROBABILITIES

Two road locations have been proposed to access a proposed timber landing (Fig 1). A Level 1 Stability Analysis (LISA) has been performed to give the average probabilities of slope failure [P(A)] for the two map units crossed by the two road locations. Figures 2 and 3 show the input values and results of the Level 1 Analyses. The percent road length crossing draws, sideslopes, and ridge noses [P(Bi)] has been determined for each route (Table 1). Table 2 gives the average unit road construction costs per mile to be used in the analysis.

Let A = Event of slope failure in the map unit from LISA

Let B1 = Event of a draw (in % road length / 100)

Let B2 = Event of a sideslope (in % road length / 100)

Let B3 = Event of a ridge nose (in % road length / 100)

P(Bi/A) = Given that a landslide has occured, the probability that the landslide is in i=1) a draw, i=2) a sideslope, or i=3) a ridge nose. These values can be obtained from a landslide inventory.

P(A/Bi) = The probability of slope failure given that you are in i=1) a draw, i=2) a sideslope, or i=3) a ridge nose. We are interpreting P(A/Bi) as the expected percent length of unstable road.

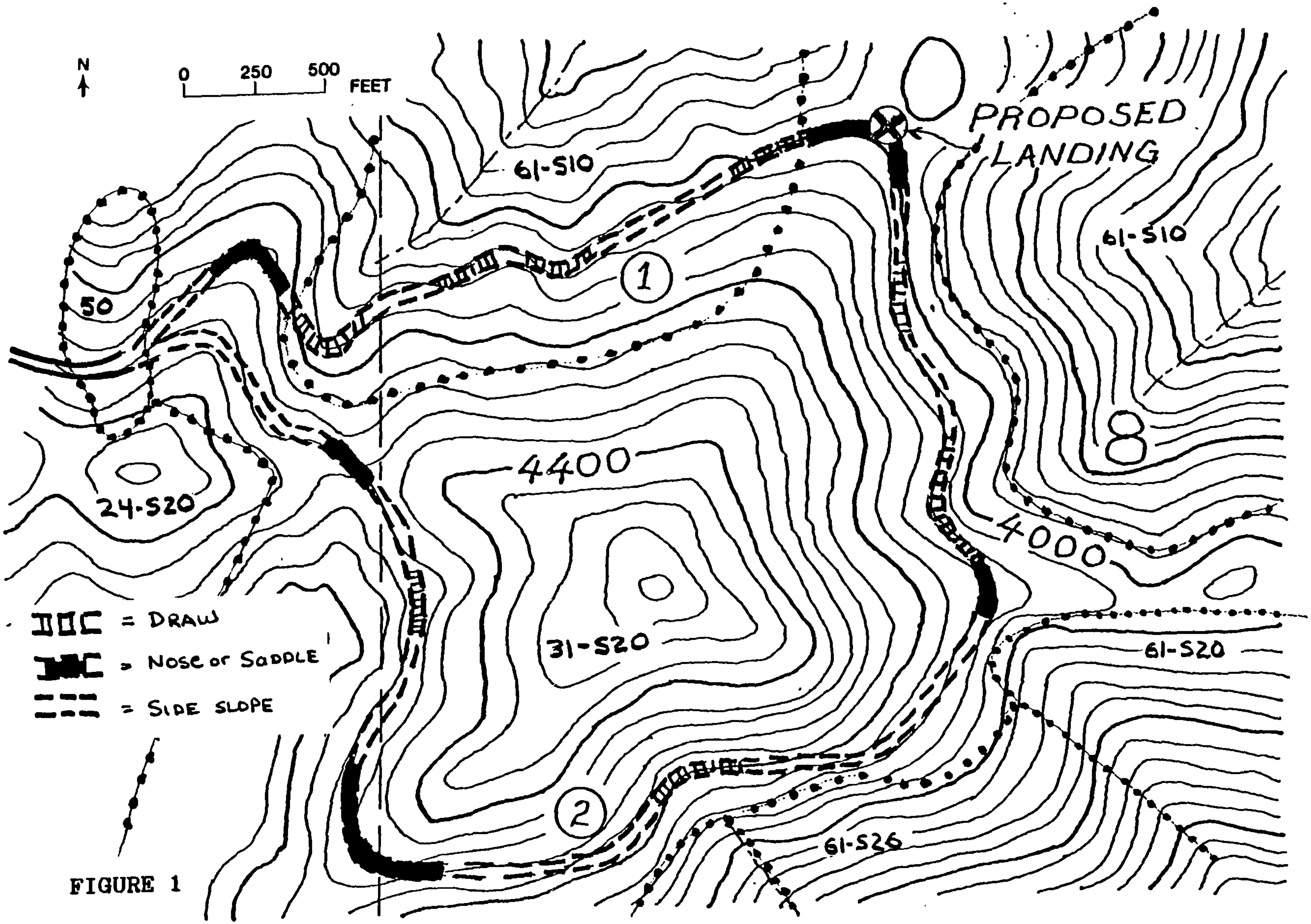

N
0
250
500
FEET
PROPOSED
LANDING
61-S10
61-S10
50
1
4400
24-S20
4000
8
= DRAW
= Nose or Saddle
= Side slope
31-S20
61-S20
2
61-S26

FIGURE 1

```
LEVEL I STABILITY ANALYSIS FOR 31-S20

 OPERATOR    : CJH
 DATE / TIME : 03-05-1987     10:28
 MPU   FILE  : CNF.MPU
 # OF SAMPLES: 1000

 Probability of failure     .049


INPUT PARAMETERS
================

 SITE  FILE  : 31-S20.SIT
      SOIL DEPTH       (ft)  HISTOGRAM.  4 CELLS
                  MIN          MAX    PERCENT
                 3.00        5.00      10.00
                 5.00        8.00      75.00
                 8.00       10.00      10.00
                10.00       17.00       5.00
      SLOPE              (%)   TRIANGULAR.
         MIN.:     30.00  MAX.:     60.00  APEX:     50.00
      TREE SURCHARGE   (psf) NORMAL.
         MEAN:     50.00  S.D.:     10.00
      ROOT COHESION    (psf) NORMAL.
         MEAN:     94.00  S.D.:     20.00

 MATERIAL  FILE  : SM-MICA.MTL
      FRICTION ANGLE   (deg) BETA.
         MIN.:     27.00  MAX.:     34.00     P:      3.00    Q:      1.50
      SOIL COHESION    (psf) UNIFORM.
         MIN.:       .00  MAX.:     40.00
      DRY DENSITY      (pcf) TRIANGULAR.
         MIN.:     73.00  MAX.:    117.00  APEX:     96.00
      MOISTURE CONTENT (%)   NORMAL.
         MEAN:     15.00  S.D.:      5.00
   SPECIFIC GRAVITY OF SOLIDS      2.660
   R (tan PHI, Cs)                  .000

 GROUNDWATER FILE   : 31-S20.HYD
      dw/d RATIO                TRIANGULAR.
         MIN.:       .10  MAX.:      1.00  APEX:       .50


 DESCRIPTIVE STATISTICS
 ======================
```

	MIN	MAX	MEAN	S.D.
FACTOR OF SAFETY	.75	2.77	1.37	.27
SOIL DEPTH (ft)	3.03	16.88	6.82	2.09
SURFACE SLOPE (%)	30.43	59.88	46.56	6.05
TREE SURCHARGE (psf)	20.98	80.90	49.92	10.18
ROOT COHESION (psf)	40.00	151.82	94.66	20.52
FRICTION ANGLE (deg)			31.67	1.41
SOIL COHESION (psf)			20.00	11.55
DRY DENSITY (pcf)	73.84	115.75	95.01	8.93
MOIST DENSITY (pcf)	81.29	133.98	109.19	11.04
SAT. DENSITY (pcf)	108.48	134.63	121.69	5.57
MOISTURE CONTENT (%)	1.07	30.45	14.94	4.89
DW/D RATIO	.11	.99	.54	.19
SHEAR STRENGTH (psf)	117.70	816.77	328.10	93.77

```
  Probability of failure =    .049
```

FIGURE 2

```
LEVEL I STABILITY ANALYSIS FOR 61-S10

 OPERATOR    : CJH
 DATE / TIME : 03-05-1987     10:23
 MPU   FILE  : CNF.MPU
 # OF SAMPLES: 1000

 Probability of failure     .360


INPUT PARAMETERS
================

 SITE  FILE  : 61-S10.SIT        (modified)
      SOIL DEPTH        (ft)  HISTOGRAM.  4 CELLS
                  MIN         MAX    PERCENT
                 3.00       5.00      15.00
                 5.00       8.00      75.00
                 8.00      10.00       7.00
                10.00      17.00       3.00
      SLOPE             (%)    TRIANGULAR.
         MIN.:     40.00  MAX.:    80.00  APEX:     60.00
      TREE SURCHARGE    (psf) NORMAL.
         MEAN:     50.00  S.D.:    10.00
      ROOT COHESION     (psf) NORMAL.
         MEAN:     94.00  S.D.:    20.00

 MATERIAL  FILE   : SM-MICA.MTL
      FRICTION ANGLE    (deg) BETA.
         MIN.:     27.00  MAX.:    34.00      P:      3.00    Q:      1.50
      SOIL COHESION     (psf) UNIFORM.
         MIN.:       .00  MAX.:    40.00
      DRY DENSITY       (pcf) TRIANGULAR.
         MIN.:     73.00  MAX.:   117.00  APEX:     96.00
      MOISTURE CONTENT (%)    NORMAL.
         MEAN:     15.00  S.D.:     5.00
   SPECIFIC GRAVITY OF SOLIDS         2.660
   R (tan PHI, Cs)                     .000

 GROUNDWATER FILE   : 61-S10.HYD        (modified)
      dw/d RATIO              TRIANGULAR.
         MIN.:       .10  MAX.:     1.00  APEX:       .70


DESCRIPTIVE STATISTICS
======================

                                 MIN         MAX        MEAN        S.D.

FACTOR OF SAFETY                 .61        1.93        1.08         .20
SOIL DEPTH      (ft)            3.00       16.88        6.47        1.94
SURFACE SLOPE   (%)            40.20       79.75       60.04        8.36
TREE SURCHARGE  (psf)          21.64       80.90       50.30       10.35
ROOT COHESION   (psf)          32.20      155.80       93.40       19.44
FRICTION ANGLE  (deg)                                  31.67        1.41
SOIL COHESION   (psf)                                  20.00       11.55
DRY   DENSITY   (pcf)          74.84      116.88       95.72        9.15
MOIST DENSITY   (pcf)          81.14      134.97      109.97       11.46
SAT.  DENSITY   (pcf)         109.11      135.34      122.14        5.71
MOISTURE CONTENT (%)             .36       30.45       14.87        4.73
DW/D RATIO                       .14         .99         .60         .18
SHEAR STRENGTH  (psf)         102.73      743.46      277.92       86.27

 Probability of failure =    .360
```

FIGURE 3

Table 1. Length of road, P(Bi), and P(A/Bi) in each landform.

	Route 1				Route 2		P(Bi/A)
	Length, ft		P(Bi)		Length, ft	P(Bi)	
	61-S10	31-S20	61-S10	31-S20	31-S20		
Draw	990	0	.490	.000	1305	.195	0.80
Side	1030	390	.510	.382	4195	.626	0.19
Nose	0	630	.000	.618	1200	.179	0.01
Total	2020	1020	1.000	1.000	6700	1.000	1.00

Table 2. Average road construction costs/mile.

Map Unit	Stable Road *	Additional cost for Unstable Road **
31-S20	$21,000	$681,000
61-S10	$32,000	$681,000

* Based on values from the R-1 Clearwater National Forest Land System Inventory (LSI) Review Draft, 1983.

** Based on $27,000 per site average stabilization cost from R-6 Geotechnical Drilling Study, 1986.

$$\frac{\$27{,}000/\text{site}}{200\ \text{ft/site}} * 5280\ \text{ft/mi} = \$712{,}800/\text{mi}$$

Additional stabilization costs = $712,800 - 32,000 = $ 680,800/mi.

Use conditional probabilities [P(A/Bi)] to estimate the probabilities of failure in draws, sideslopes and ridge noses from the Level 1 results. Calculate the expected cost of road construction for each landform type and determine which route has the lowest total expected cost.

$$\text{Expected cost} = \begin{array}{c}\text{road}\\ \text{length (mi)}\end{array} \left(\begin{array}{c}\text{cost/mile}\\ \text{for stable}\\ \text{road}\end{array} + \begin{array}{c}\text{add. cost/mile}\\ \text{for unstable}\\ \text{road}\end{array} * \begin{array}{c}\text{expected \%}\\ \text{length of}\\ \text{unstable road}\end{array} \right)$$

SOLUTION

Route 1

61-S10

1) $P(A/B1) = \frac{P(B1/A)\ P(A)}{P(B1)} = \frac{(.80)(.360)}{(.49)} = .588$

2) $P(A/B2) = \frac{P(B2/A)\ P(A)}{P(B2)} = \frac{(.19)(.360)}{(.51)} = .134$

31-S20

3) $P(A/B2) = \frac{P(B2/A)\ P(A)}{P(B2)} = \frac{(.19)(.049)}{(.382)} = .024$

4) $P(A/B3) = \frac{P(B3/A)\ P(A)}{P(B3)} = \frac{(.01)(.049)}{(.618)} = .001$

EXPECTED COSTS

1) 990 ft/5280 fpm [$32,000/mi + $681,000/mi * .588] = $ 81,080
2) 1030 ft/5280 fpm [$32,000/mi + $681,000/mi * .134] = $ 24,044
3) 390 ft/5280 fpm [$21,000/mi + $681,000/mi * .024] = $ 2,758
4) 630 ft/5280 fpm [$21,000/mi + $681,000/mi * .001] = $ 2,587

TOTAL EXPECTED COST = $110,469

Route 2

1) $P(A/B1) = \frac{P(B1/A)\ P(A)}{P(B1)} = \frac{(.80)(.049)}{(.195)} = .201$

2) $P(A/B2) = \frac{P(B2/A)\ P(A)}{P(B2)} = \frac{(.19)(.049)}{(.626)} = .015$

4) $P(A/B3) = \frac{P(B3/A)\ P(A)}{P(B3)} = \frac{(.01)(.049)}{(.179)} = .003$

EXPECTED COSTS

1) 1305 ft/5280 fpm [$21,000/mi + $681,000/mi * .201] = $ 39,021
2) 4195 ft/5280 fpm [$21,000/mi + $681,000/mi * .015] = $ 24,800
3) 1200 ft/5280 fpm [$21,000/mi + $681,000/mi * .003] = $ 5,237

TOTAL EXPECTED COST = $ 69,058

CONCLUSION

Route 2 has the lower expected cost. Thus the prefered decision is to use Route 2.

PROBLEM 4
DECISION ANALYSIS USING LEVEL 2 STABILITY ANALYSIS
A DISCUSSION OF PROCEDURE

The purpose of this discussion is to introduce how the probabilites of cut and fill failure from a Level II Stability Analysis might be used.

To obtain the necessary data, a field reconnaissance of one or more proposed road locations would be necessary to classify each route into like segments. Better estimates and measurements of the input parameters; particularly slope, soil depth, ground water characteristics, and shear strength of the materials; should be made for each segment. A Level II stability analysis would then be performed on a representative cross section from each segment to estimate the probabilities of cut and fill failure. Also an infinite slope analysis using the LISA program should be performed with the information obtained in the reconnaissance survey to estimate the probability of failure of the natural slope above and below each representative cross section.

The Level II stability analysis uses critical height and Cousin's Factor of Safety methods in estimating the probability of failure. Since these methods assume a rotational failure surface, the probabilities of failure strickly apply only to circular failures. The probability of natural failure may be related to the probability of translational failure which intersect the road.

COSTS

The cost of stabilizing a failure depends on the failure mode (i.e. rotational or translational) and the size of the failure. Since the analysis does not tell us about the size of failure, or how many failure sites might occur, the cost per foot to stabilize different failures should be taken from past records. For example, if the average cost to stabilize rotational cut failures was $15,000 and the average road length involved in failure was 150 feet, the cost per foot is $100. These costs are in addition to the basic road construction cost.

EXPECTED COSTS

As in Problem 3 the probabilities of failure can most usefully be interpreted as the expected percent road length involved in each mode of failure. The probability of failure times the length of the road segment is the expected length of road involved in failure. The expected length times the cost per foot gives the expected cost for that segment. The expected costs for each segment would be totalled to obtain the expected cost for the road location.

ECONOMICS FOR ROCK AGGREGATE PROBLEM

CONSTRUCTION REQUIREMENTS: 39,000 tonnes (43,000 tons),
or 15,000 cu.m. (19,600 cu.yd.)

VALUE OF AGGREGATE AT PIT: $4.40/tonne

HAULING COST: $0.40/cu.m-km ($0.50/cu.yd.-mi)

COST OF GEOPHYSICS (SEISMIC/RESISTIVITY), 0.60 RELIABLE: $1500

COST OF DRILLING, 0.90 RELIABLE: $6000 (PLUS $1200 FOR SITE REHAB. IF NOT DEVEL.)

COST OF MOBILIZATION/ INITIAL PIT DEVEL.: $12,000
COST TO REMOBILIZE AND MOVE TO ALT. SITE: $14,000
COST TO REHABILITATE SEMI OR FAILED PIT: $ 3,000

	SITE 1	SITE 2
HAULING DISTANCE	12 km (7.5 mi)	22.5 km (14 mi)
INITIAL PROBABILITY VALUES: (GOOD,SEMI,FAIL)	.20 .25 .55	.25 .35 .40

<u>POSSIBLE OUTCOME</u>

	SITE 1	SITE 2
GOOD SOURCE	39K(4.40) = 171.6K - <u>15K(.4)(12) = 72K</u> **99.6K**	171.6K <u>15K(.4)(22.5) = 135K</u> **60.6K**
SEMI SOURCE/MOVE; ALT. OK	171.6K - 36K - 67.5K - 17K = **51.1K for both**	
SEMI SOURCE/MOVE; ALT. FAIL	85.8K - 36.0K - <u>20.0K</u> **29.8K**	85.8K - 67.5K - <u>20.0K</u> - **1.7K**
FAIL SOURCE/MOVE; ALT. GOOD	60.6K - <u>17.0K</u> **43.6K**	99.6K - <u>17.0K</u> **82.6K**
FAIL SOURCE/MOVE; ALT. SEMI	- **1.7K**	**29.8K**
FAIL SOURCE/MOVE; ALT. FAIL	- 20K - 10K(nonprod. delay) = - **30K for both**	
DRILL/MOVE; ALT. GOOD	60.6K-1.2K=**59.4K**	99.6K-1.2K=**98.4K**
DRILL/MOVE; ALT. SEMI	18.3K-4.2K=**14.1K**	49.8K-4.2K=**45.6K**
DRILL/MOVE; ALT. FAIL	-4.2K - 5K = **-9.2K for both**	

ROCK AGGREGATE SOURCE – PROBABILITY CALCULATIONS FOR SITE 1

LET: A_1 = event of a good source; A_2 = " semi source; A_3 = " poor source

B_1 = event that tests ind. good; B_2 = " semi; B_3 = " poor

$P(A_1) = .20 \quad P(A_2) = .25 \quad P(A_3) = .55$

$$P(B_i|A_i) = \begin{array}{cc} \underline{\text{Geoph.}} & \underline{\text{Drill.}} \\ .60 & .90 \end{array}$$

GEOPH.

$$P(B_1) = P(B_1|A_1)P(A_1) + \tfrac{1}{2}P(B_1|\bar{A}_1)P(\bar{A}_1)$$
$$= .60(.20) + \tfrac{1}{2}(.40)(.80) = \underline{.280}$$
$$P(B_2) = .60(.25) + \tfrac{1}{2}(.40)(.75) = \underline{.300}$$
$$P(B_3) = .60(.55) + \tfrac{1}{2}(.40)(.45) = \underline{.420}$$

$$P(A_1|B_1) = \frac{P(B_1|A_1)P(A_1)}{P(B_1)} = \frac{.6(.20)}{.28} = \underline{.428}$$
$$P(A_2|B_1) = \frac{\tfrac{1}{2}(.4)(.25)}{.28} = \underline{.179}$$
$$P(A_3|B_1) = \frac{\tfrac{1}{2}(.4)(.55)}{.28} = \underline{.393}$$

$$P(A_1|B_2) = \frac{\tfrac{1}{2}(.4)(.20)}{.30} = \underline{.133}$$
$$P(A_2|B_2) = \frac{.6(.25)}{.30} = \underline{.500}$$
$$P(A_3|B_2) = \frac{\tfrac{1}{2}(.4)(.55)}{.30} = \underline{.367}$$

DRILLING

$$P(B_1) = .90(.20) + \tfrac{1}{2}(.10)(.80)$$
$$= \underline{.220}$$
$$P(B_2) = .90(.25) + \tfrac{1}{2}(.10)(.75) = \underline{.263}$$
$$P(B_3) = .9(.55) + \tfrac{1}{2}(.1)(.45) = \underline{.517}$$

$$P(A_1|B_1) = \frac{.9(.20)}{.220} = \underline{.818}$$
$$P(A_2|B_1) = \frac{\tfrac{1}{2}(.1)(.25)}{.220} = \underline{.057}$$
$$P(A_3|B_1) = \frac{\tfrac{1}{2}(.1)(.55)}{.220} = \underline{.125}$$

$$P(A_1|B_2) = \frac{\tfrac{1}{2}(.1)(.20)}{.263} = \underline{.038}$$
$$P(A_2|B_2) = \frac{.9(.25)}{.263} = \underline{.857}$$
$$P(A_3|B_2) = \frac{\tfrac{1}{2}(.1)(.55)}{.263} = \underline{.105}$$

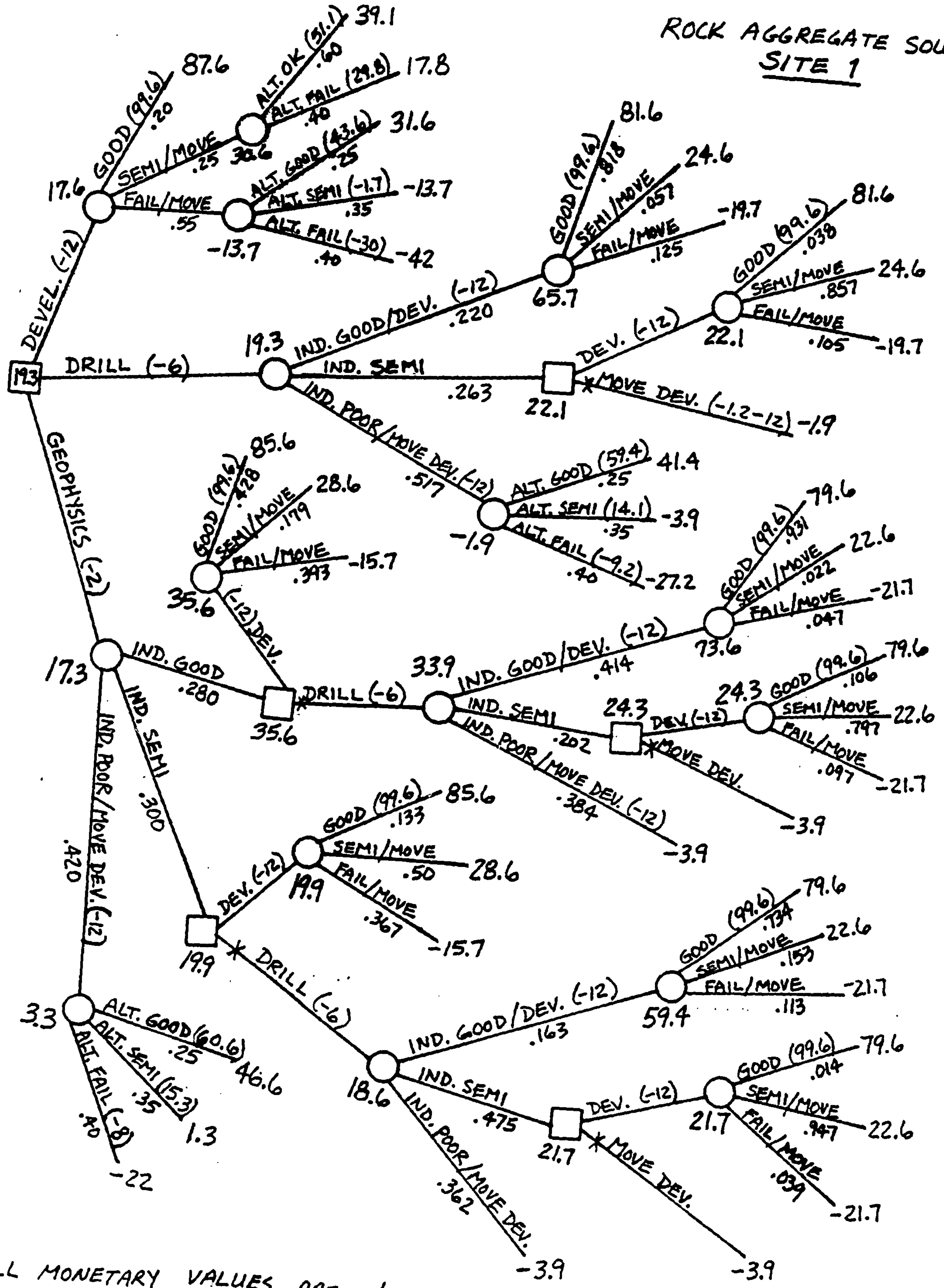
TO CONDITION PROB. VALUES FOR DRILLING AFTER GEOPH. INDICATES (I.E., DUAL CONDITIONING)

	$P(A_1)$	$P(A_2)$	$P(A_3)$
GOOD	.428	.179	.393
SEMI	.133	.50	.367
POOR	.095	.119	.786

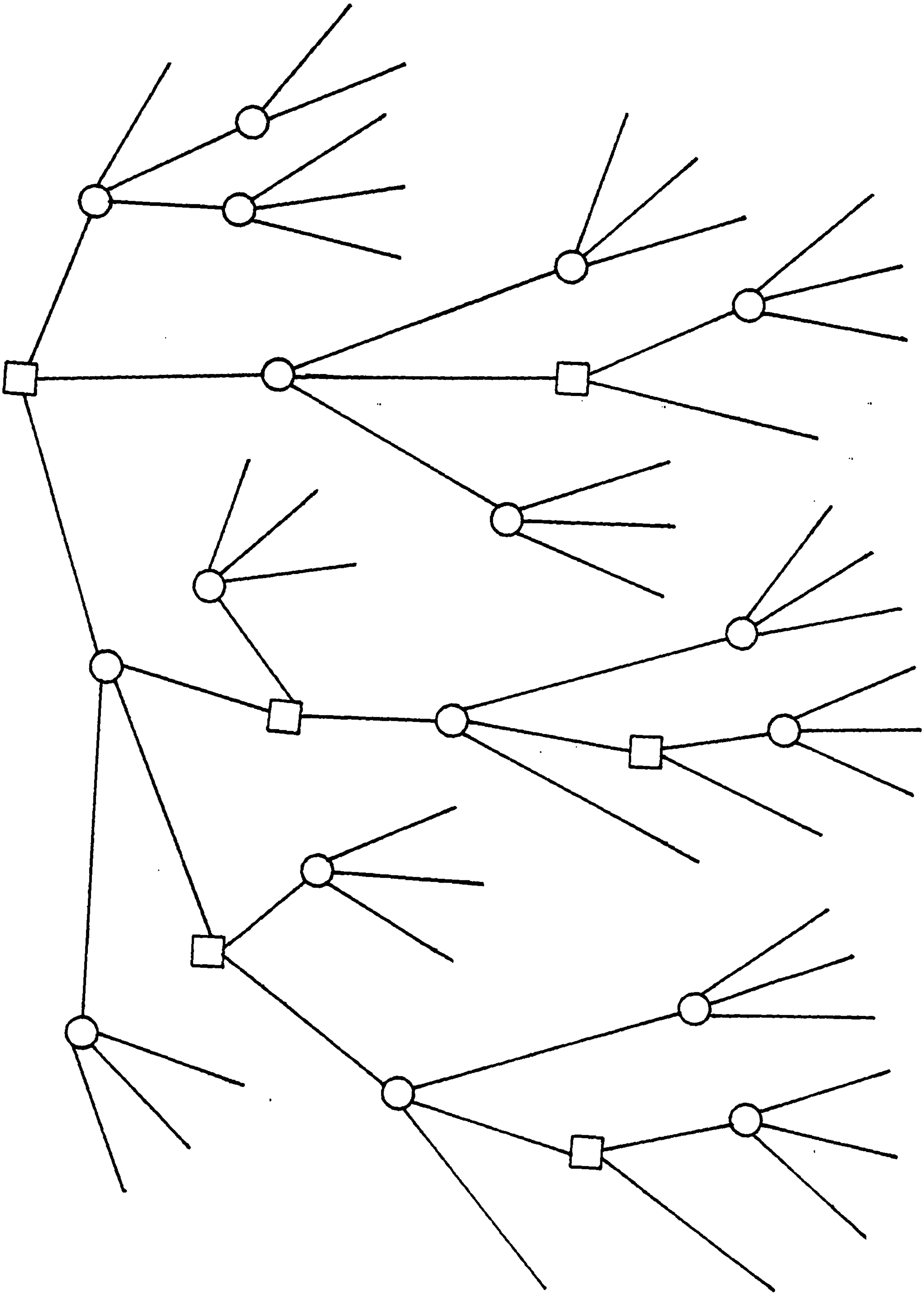
USE

NOT NEEDED IN DEC. TREE

ROCK AGGREGATE SOURCE
SITE 1

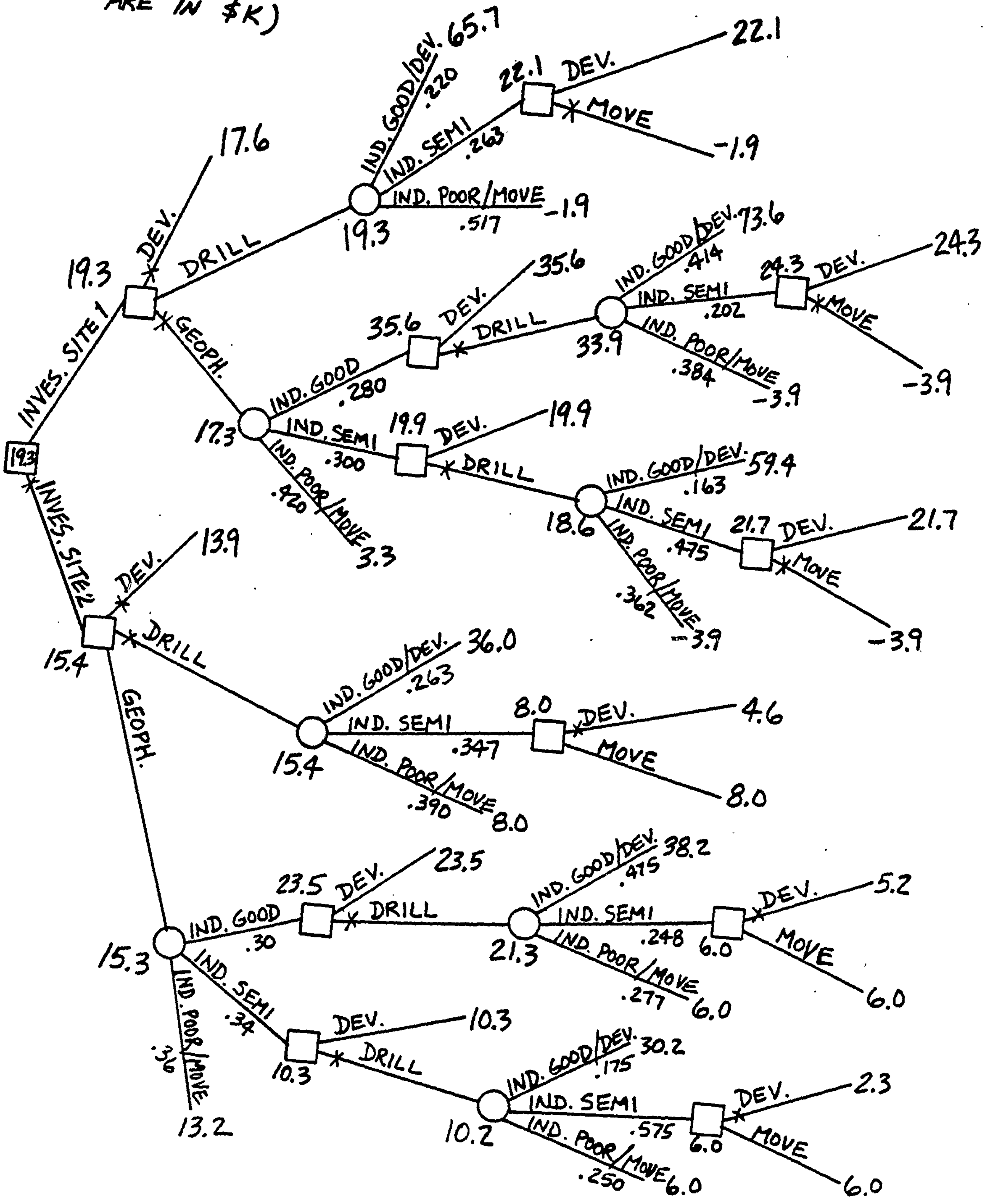


ALL MONETARY VALUES ARE $K.



SUMMARY DECISION TREE FOR ROCK AGGREGATE SOURCE

(MONETARY VALUES ARE IN $K)



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C
C*** FORTRAN77 CODE FOR COND. PROB. VALUES AND FOR UPDATING THEM ***
C
      PROGRAM CONDPR
C
      INTEGER N
      REAL PA(5),PB(5),PBA(5,5),PAB(5,5),SUM
      CHARACTER*15 OFILE
C
      WRITE(*,*) '* PROGRAM TO CONDITION PRIOR PROBABILITY VALUES *'
      WRITE(*,110)
  110 FORMAT(/,' ENTER NO. OF EVENTS/OUTCOMES:  ',\)
      READ(*,*) N
      WRITE(*,120)
  120 FORMAT(/,' ENTER IN ORDER THE PRIOR PROB. VALUES, P[Ai]:')
      READ(*,*) (PA(I),I=1,N)
C
      WRITE(*,130)
  130 FORMAT(/,' ENTER IN ORDER THE COND. PROB. VALUES, P[Bj\Ai]:')
        DO 10 I=1,N
        WRITE(*,132) I
  132   FORMAT(' FOR B',I1,':  ',\)
   10   READ(*,*) (PBA(I,J),J=1,N)
C
C*** CALC. TOTAL PROB. VALUES FOR Bj'S ***
C
        DO 30 J=1,N
        SUM=0.
          DO 20 I=1,N
   20     SUM=SUM + PBA(J,I)*PA(I)
   30   PB(J)=SUM
C
C*** CALC. UPDATED PROB. VALUES VIA BAYES THEOREM ***
C
        DO 50 J=1,N
          DO 40 I=1,N
   40     PAB(I,J)=PBA(J,I)*PA(I)/PB(J)
   50   CONTINUE
C
      WRITE(*,140)
  140 FORMAT(//,' ENTER NAME OF OUTPUT FILE:  ',\)
      READ(*,'(A)') OFILE
      OPEN(8,FILE=OFILE,STATUS='NEW')
C
      WRITE(8,150)
  150 FORMAT(/' ** OUTPUT FROM CONDITIONAL PROB. CALCULATIONS **',/)
      WRITE(8,155)
  155 FORMAT(/,T5,'PRIOR INFORMATION',T29,'NEW PROBABILITY VALUES',/,
     &T5,'P[Ai]    P[Bj\Ai]',T29,'P[Bj]     P[Ai\Bj]',/)
C
        DO 60 I=1,N
        WRITE(8,160) PA(I),(PBA(I,J),J=1,N),PB(I),(PAB(I,J),J=1,N)
  160   FORMAT(13F6.3)
   60   CONTINUE
C
      STOP
      END
```